Engineering, Operations & Technology
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Anisotropic Adaptive Mesh Results for the Third High Lift Prediction Workshop (HiLiftPW-3)

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Boeing Research and Technology

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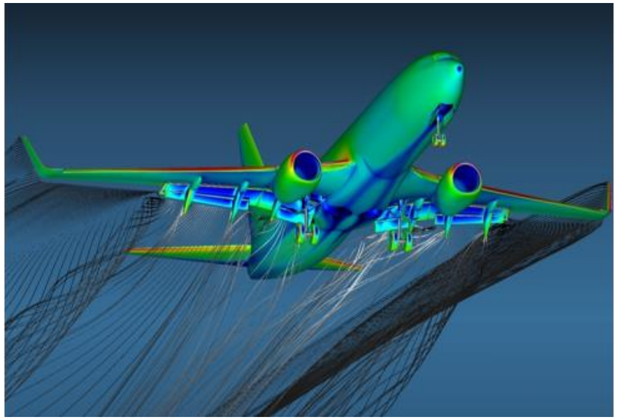
Outline

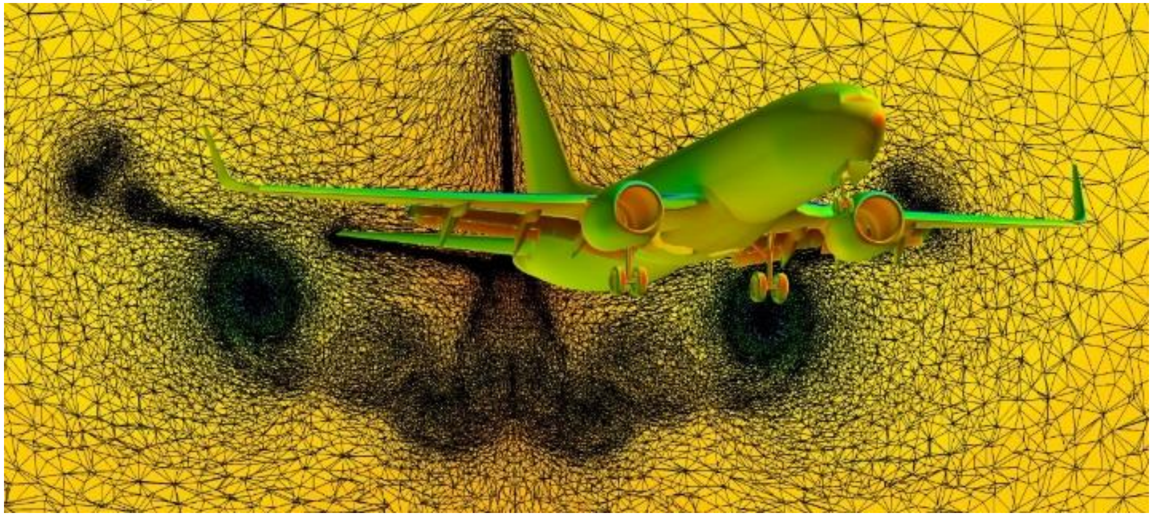
- **Introduction - Meshing for High-Lift Analysis**
- **Overview of Mesh and Flow Solver Toolsets**
- **HL-CRM Results**
- **JSM Results**
- **Conclusions**

CFD High-Lift Prediction



- **Typically Occurs During Take Off and Landing**
  - ✓ Deployed slats, flaps and landing gear
  - ✓ High angle of attack
  - ✓ Complex interaction of flow features
- **Computational Modeling Challenges**
  - ✓ Flow complexity pushes limits of physical models
  - ✓ Large regions of separated flow can challenge steady-state numerics
  - ✓ Flow feature locations/strengths are unknown
  - ✓ Features vary with run conditions
- **Traditional Mesh Approach**
  - ✓ Resolution set by educated guess and best practices
  - ✓ One set of meshes used for entire flight envelope
  - ✓ Mesh refinement study seldom done as standard practice
  - ✓ Difficult to control mesh resolution/quality in tight geometric regions

Anisotropic Adaptive Meshes



- **Automatically Coarsen/Refine and Align Mesh to Solution**
  - ✓ Reduces mesh size (number of elements) for comparable accuracy
  - ✓ Removes need to make a-priori estimate of flow features
  - ✓ Reduces labor at the expense of increased computation cost

- **Recent Progress Making Adaptive Meshing Feasible**
  - ✓ Adaptive Mesh Mechanics – **Refine** [Park 2010], **Feflo.a** [Loseille and Lohner, 2010], **EPIC** [Michal and Krakos 2012], **Omega-h** [Ibanez and Shephard 2016], **Pragmatic** [Barral, SNL 2016]
  - ✓ Error Estimates – [Venditti and Darmofal, JCP 2003], [Loseille and Alauzet, JCP 2010], …
  - ✓ Flow Solver – Advances in robust discretization, machine precision residual convergence on skewed meshes

GGNS Flow Solver
GGNS General Geometry Navier-Stokes

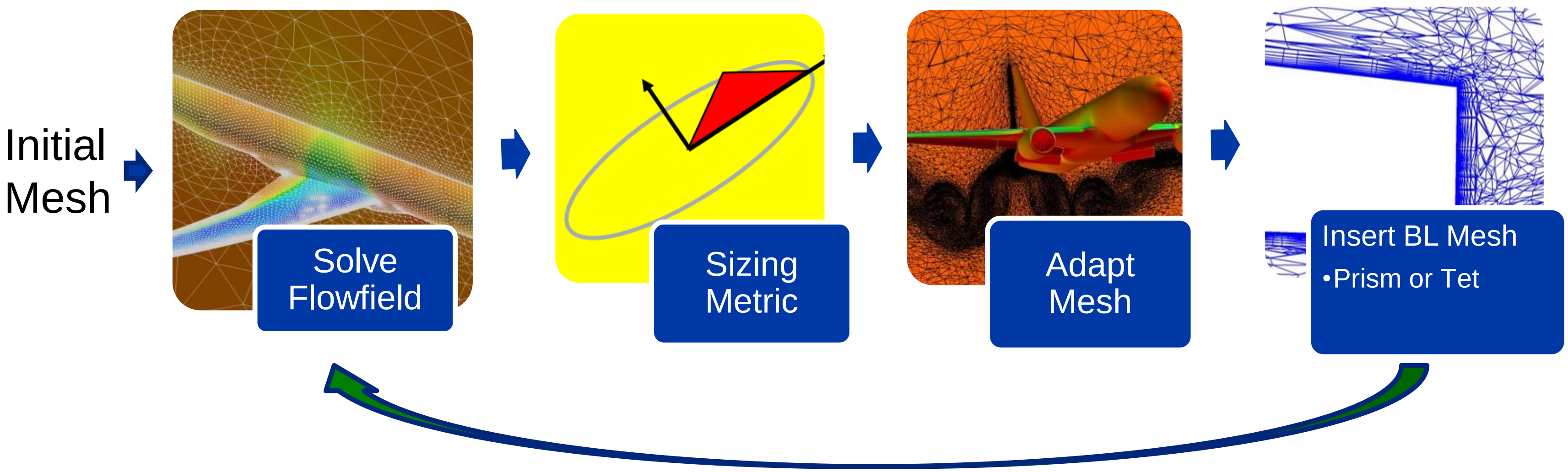
- Boeing developed CFD solver
  [Kamenetskiy, Bussoletti, Hilmes, Venkatakrishnan, Wigton, Johnson , AIAA Journal 2014]
- Stabilized finite-element SUPG, second order
- Newton-Raphson algorithm [Exact Jacobians]
- Time marching to steady state
- Linesearch
- PETSc framework for linear and non-linear solvers
- Machine-zero converged steady state solutions

For This Study

- All tetrahedral unstructured meshes
- Fully turbulent solutions : SA-QCR turbulence model

EPIC Adaptive Grid Generator
(Edge Primitive Insertion and Collapse)

- Boeing developed anisotropic metric-based mesh adaptation code
  [Michal and Krakos, AIAA 2012]



- Mesh sizing metric developed from solution error estimate
- Iterative application of edge operators (collapse, break, reconnect) to coarsen/refine surface and volume mesh
- Surface mesh maintained on IGES geometry representation
- Adaptation performed on tetrahedral mesh with optional prismatic BL grid insertion (normal spacing adapted to solver estimate of y+)

HLPW-3 Boeing Adapted Solution History

- **Prior to HLPW-3**
  - Computed HL-CRM and JAXA JSM Fixed Grid Solutions
  - Computed HL-CRM Adapted Solutions
  - JAXA JSM Nacelle On - Run in St. Louis Using Process 1
  - JAXA JSM Nacelle Off – Run in Seattle Using Process 2

- **Improvements after HLPW-3**
  - Evaluation of solutions let to modification of best practices for inserting BL mesh
  - Mesh quality improvements and solver discretization changes improve solution convergence

- **HL-CRM adaptation cases rerun with improvements**

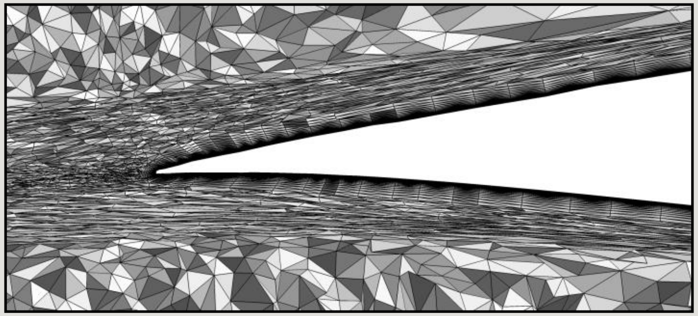
Summary of HL-CRM Cases

- Cases Computed

Grid System	Case Name	Case(s)
Committee (B1-HLCRM_UnstrTet_PW)	HLCRM Fixed Mesh	1a (full gap), 1c (partial seal)
User (a-HLCRM_AdaptedTet_EPIC)	HLCRM Adapt Mesh	1b (full gap), 1d (partial seal)

- Adaptive meshes
  - Adapted to L^4 interpolation error of the Mach Hessian
  - 40% growth between adapted mesh levels
  - Small number of near wall aligned mesh layers inserted into each adapted mesh to accelerate refinement of wall normal spacing

HL-CRM Near Wall Mesh Insertion

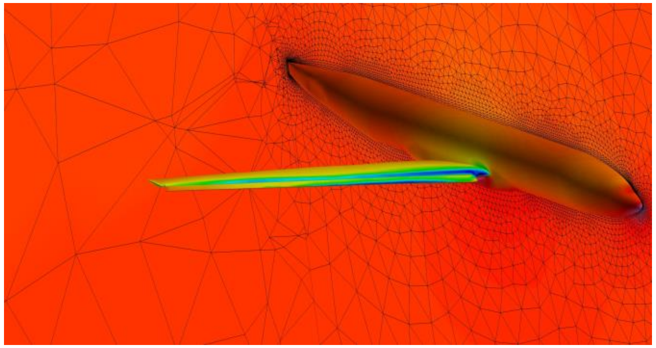


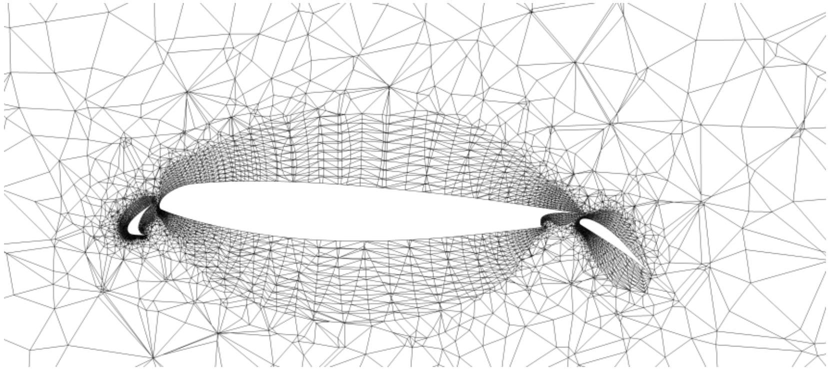
- Starting from adapted surface mesh insert layers of nodes in direction of local wall normal vector
- Wall spacing adapted to y+=0.25 at each node (computed from previous solution level)
- 2 constant layers and 16 layers with 15% geometric growth (total height y+~=100)
- Wall spacing/# layers ramped over first 3 mesh levels

HL-CRM Adaptive Mesh Sequence

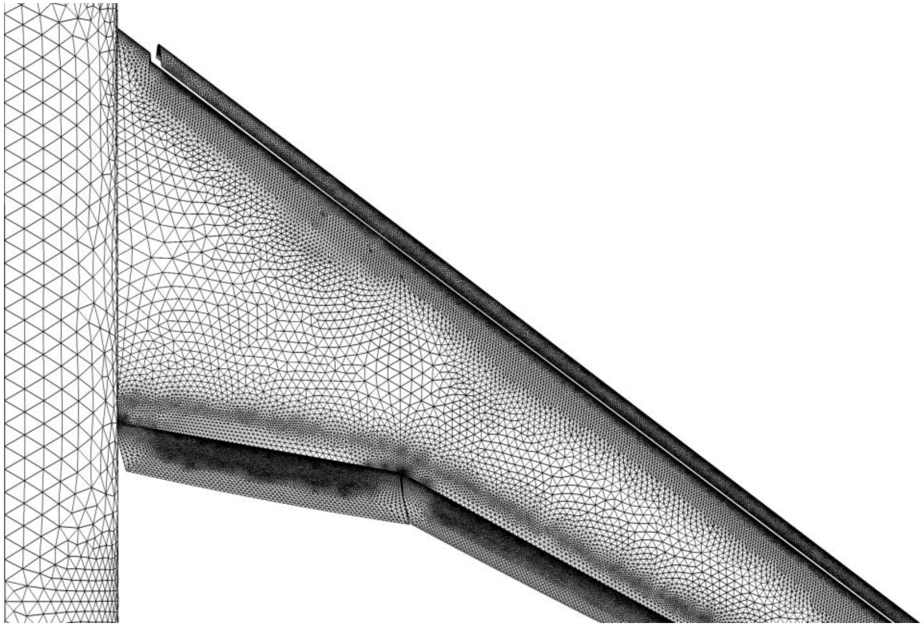
Mach 0.2, Re=3.26M, α=16^o Grid Level 0

- Generated in MADCAP[1]/AFLR[2] toolset
- Sizing based on geometry curvature plus user input to control spacing along trailing edges.
- Background function to smooth 3D distribution field
- Few layers of semi-structured volume boundary elements
- Generated in minutes





Grid 0, 0.97M Nodes , 5.4M Tetrahedra

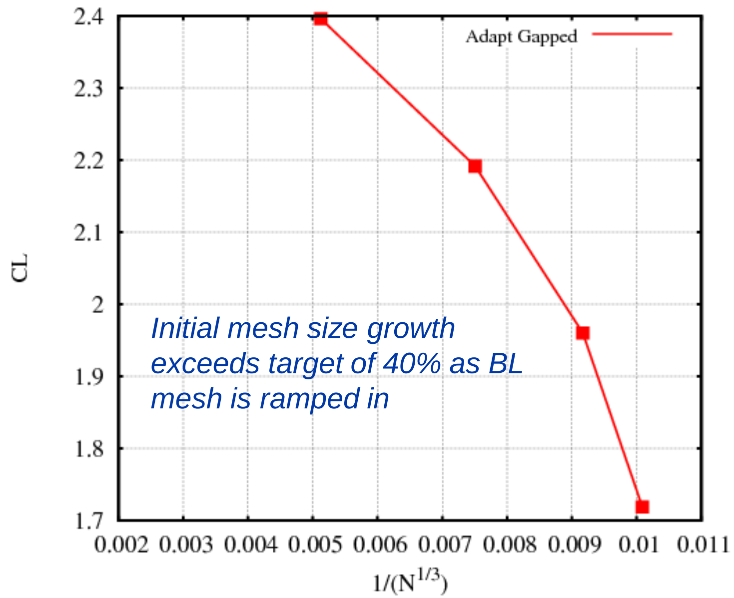


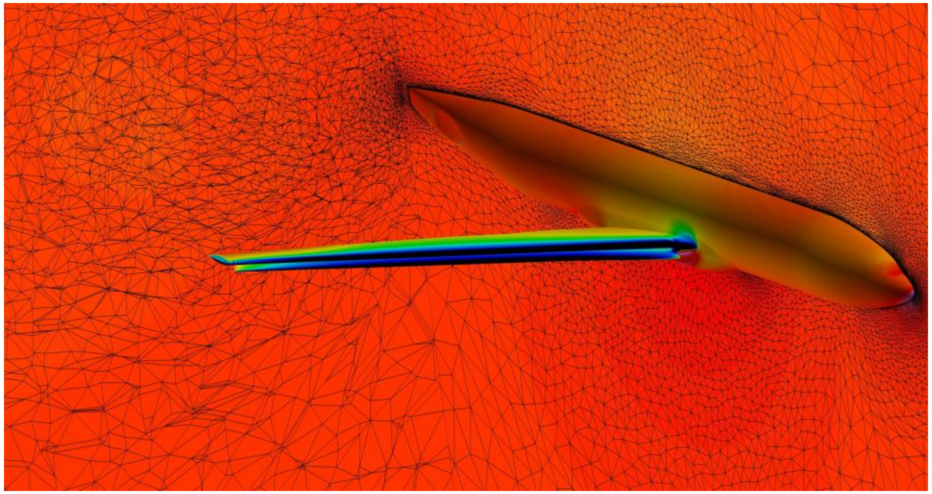
1) MADCAP – Boeing Unstructured Grid Toolset
2) AFLR – Advancing Front with Local Reconnection (Dave Marcum – Mississippi State University)

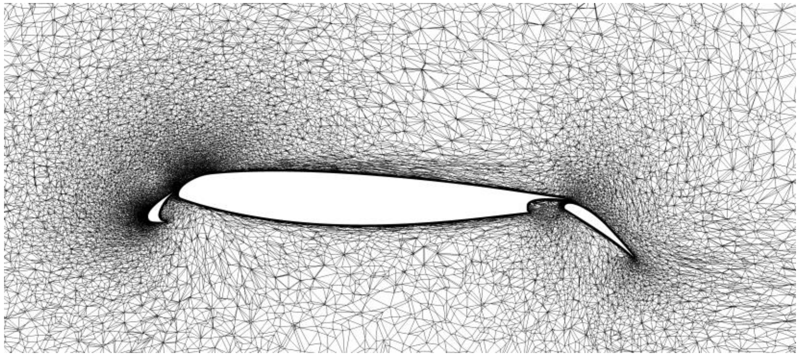
HL-CRM Adaptive Mesh Sequence

Mach 0.2, Re=3.26M, α=16^o Grid Level 3

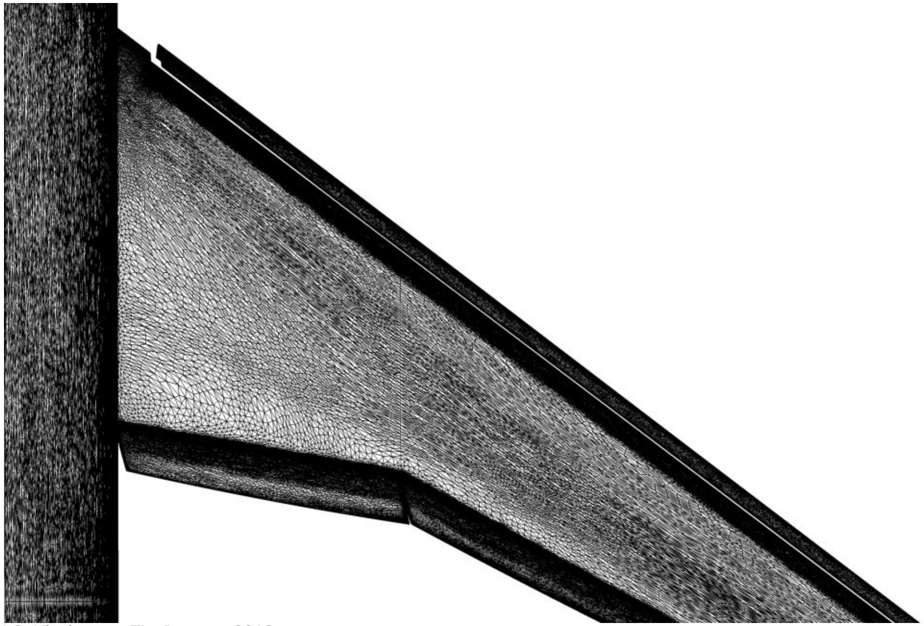
Lift Convergence





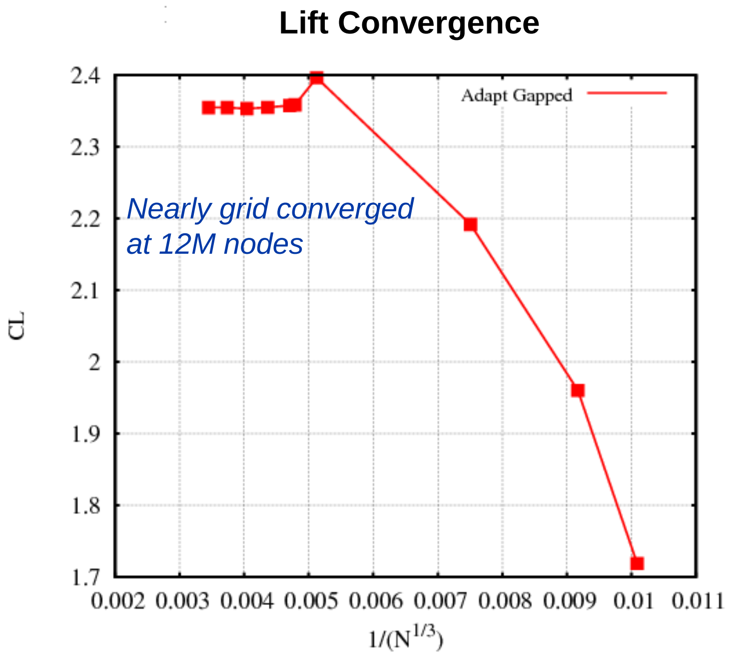


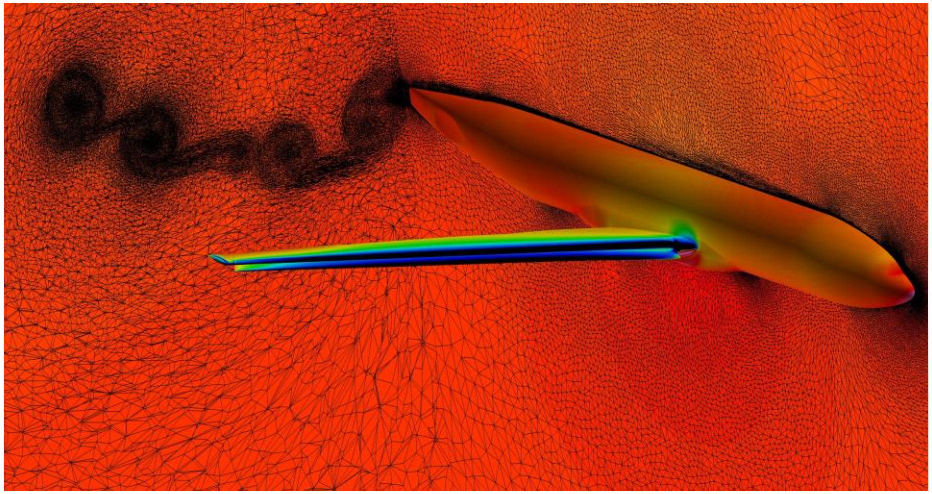
7.4M Nodes , 43.4M Tetrahedra

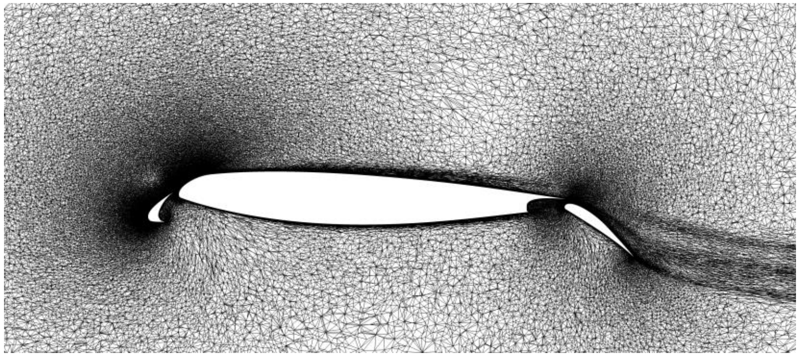


HL-CRM Adaptive Mesh Sequence

Mach 0.2, Re=3.26M, α=16º   Grid Level 9



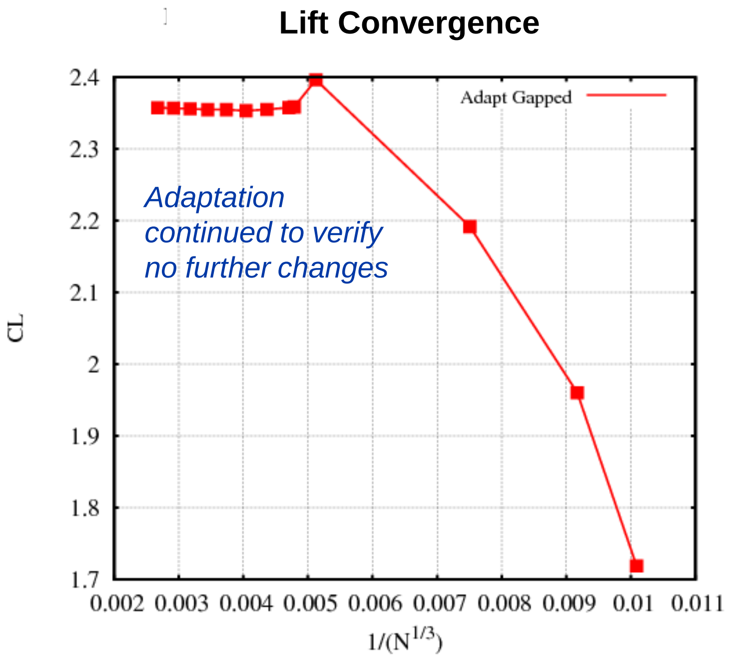


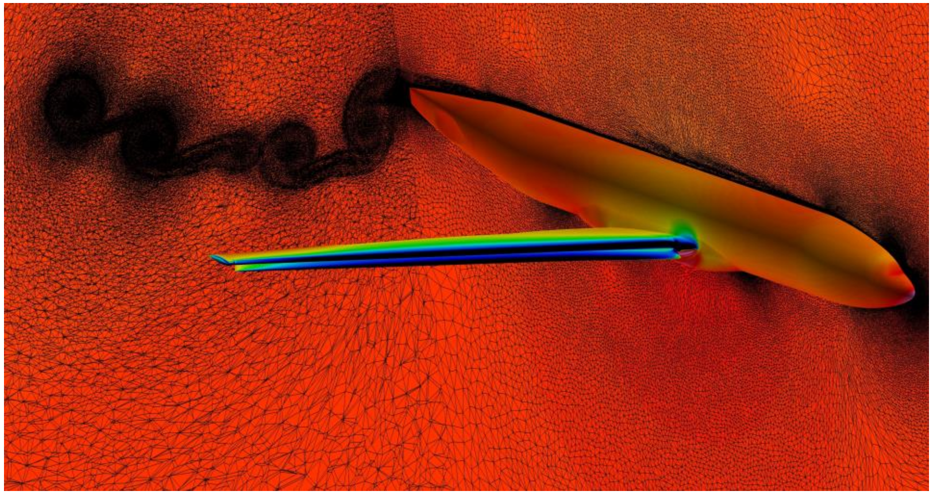


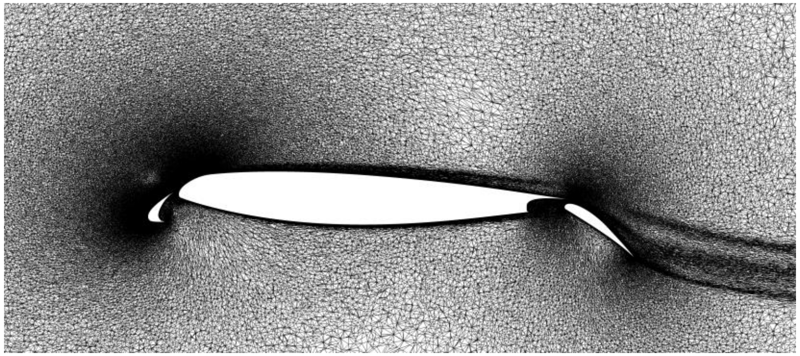
24.4M Nodes , 143.9M Tetrahedra

HL-CRM Adaptive Mesh Sequence

Mach 0.2, Re=3.26M, α=16^o Grid Level 12

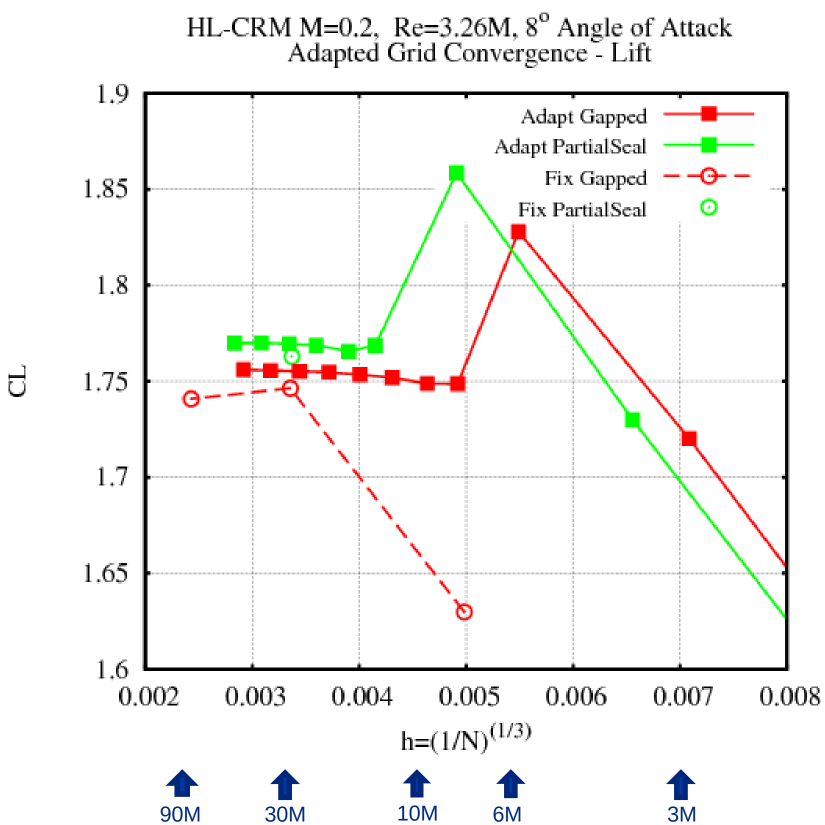


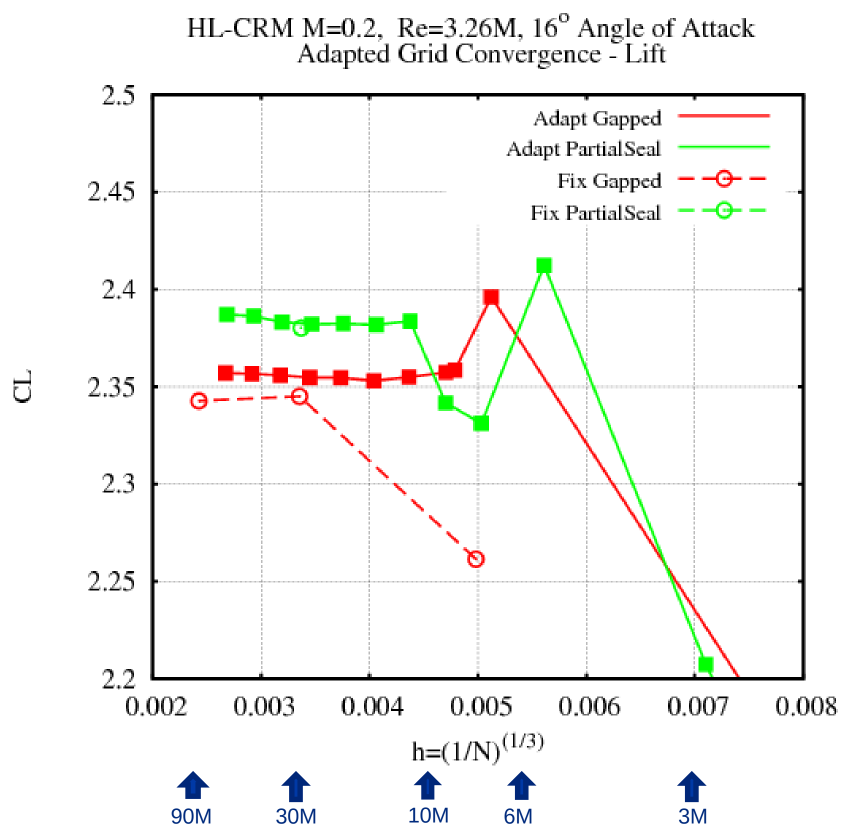




52.4M Nodes , 310M Tetrahedra

HL-CRM Mesh Convergence



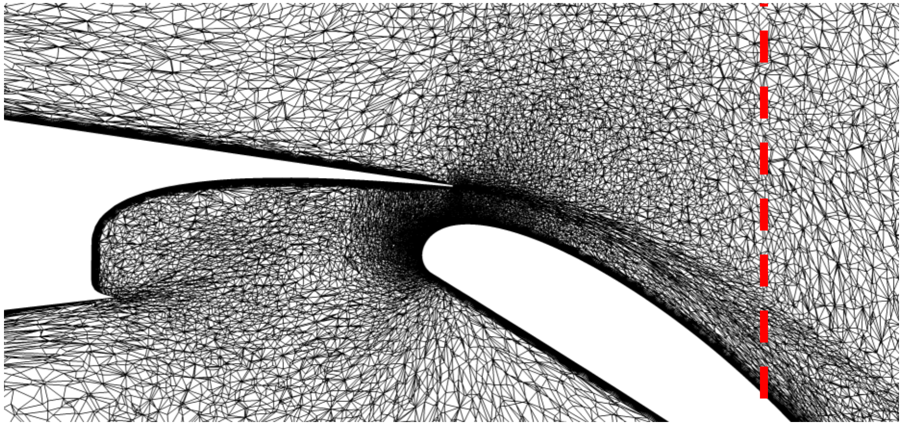


- Adapted Solutions Converge to Near Constant Lift (~ 15M DOF)
  - Slight increase in CL with grid resolution continues
  - Consistent seal-gap increment with increasing grid resolution

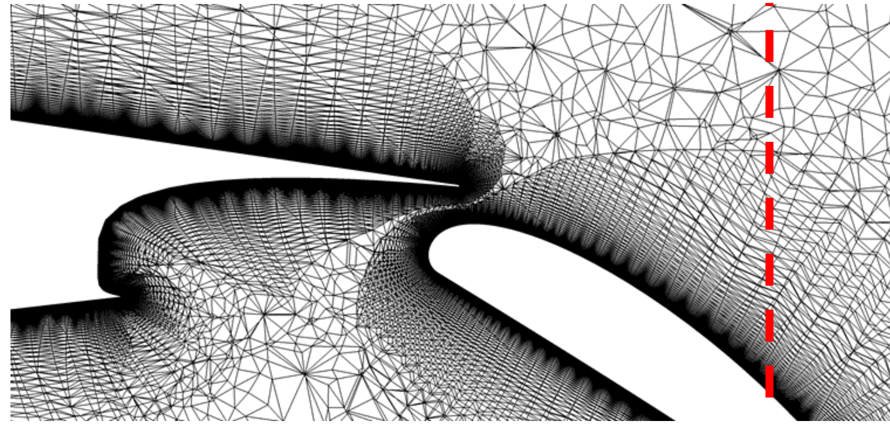
- Fixed Mesh Lift Lower and Decreasing From Medium to Fine Resolution

Velocity Profile Comparison α=16^o

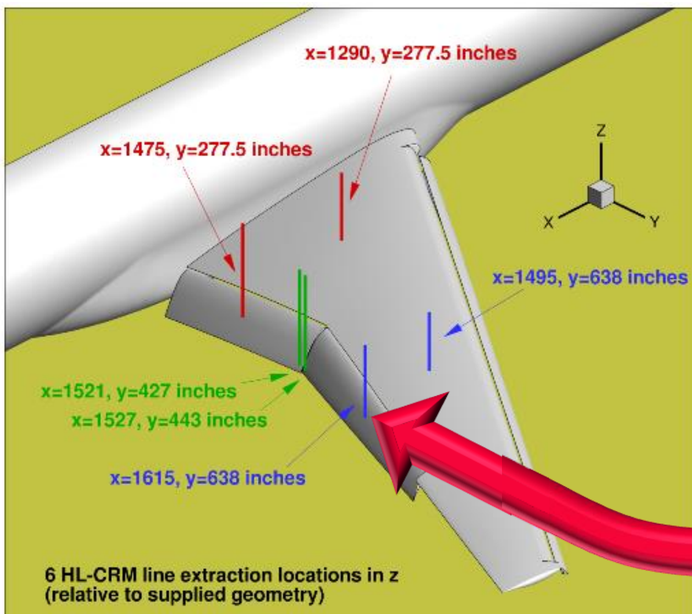
x=1615, y=638 inches

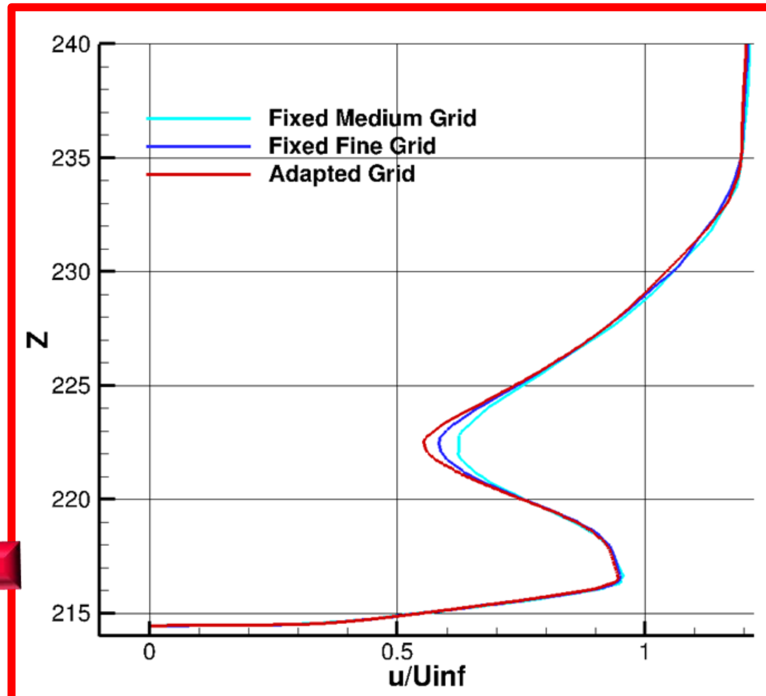


Adapted Mesh 52.4M nodes

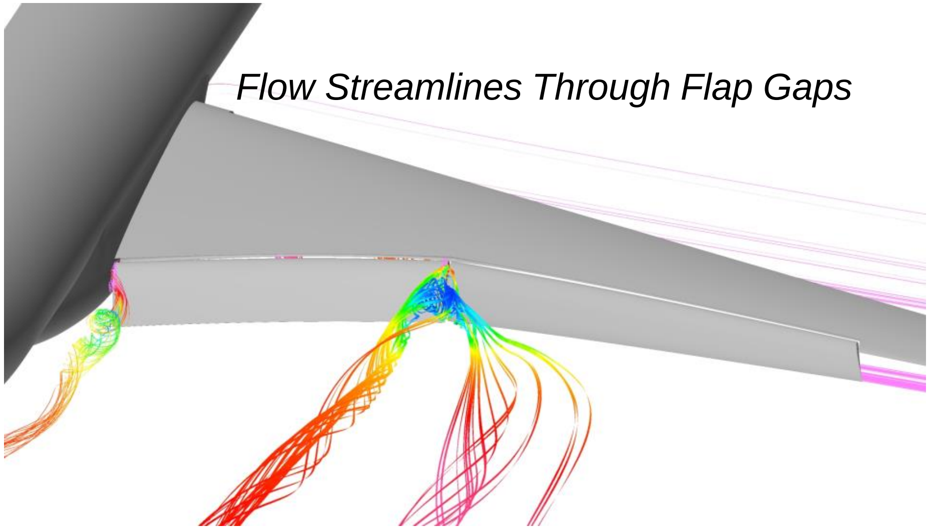


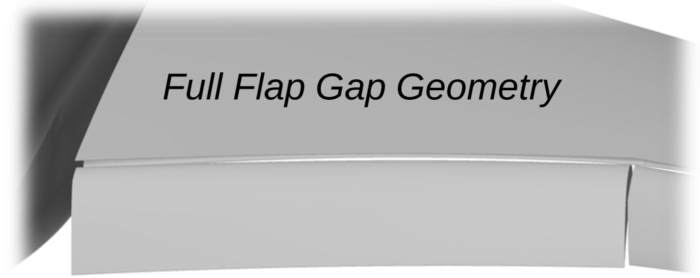
Fine Fixed Mesh 69.9M nodes



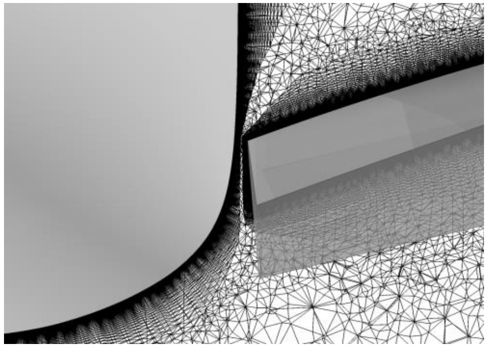


Computation of Increments
Fully Gapped/Partial Seal Flap Configurations



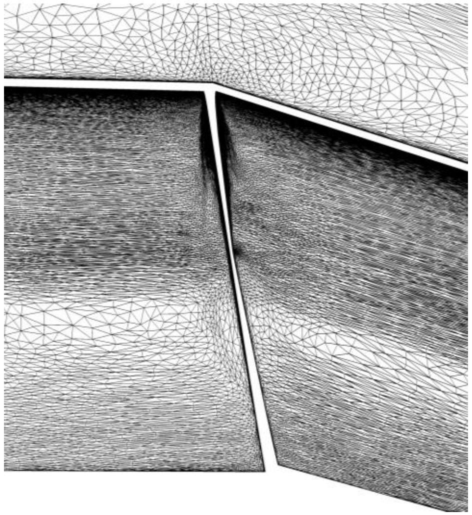
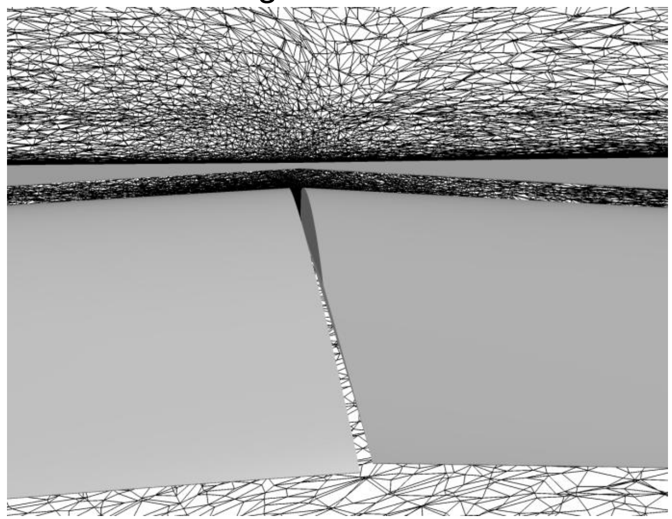
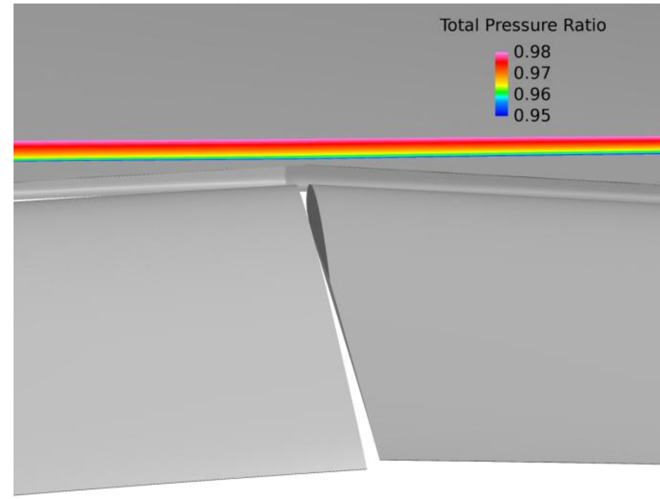


- Accurate Prediction of Flow Details Drives Gap/Seal Increment
  - Complex interaction between entrained gap flow, wakes and vortices
- Mesh Generation Challenging in Gap Regions
  - Tight proximity between flap sides
  - Compound corners
  - Resolution of off body features

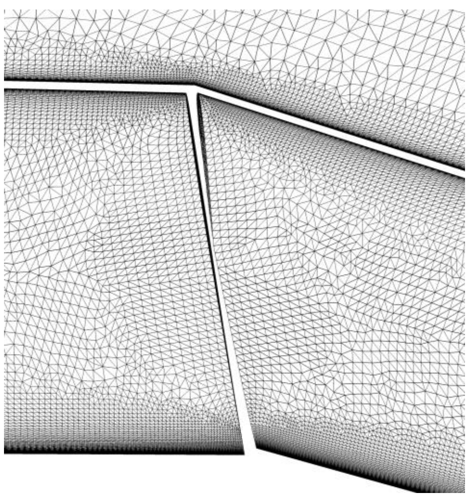
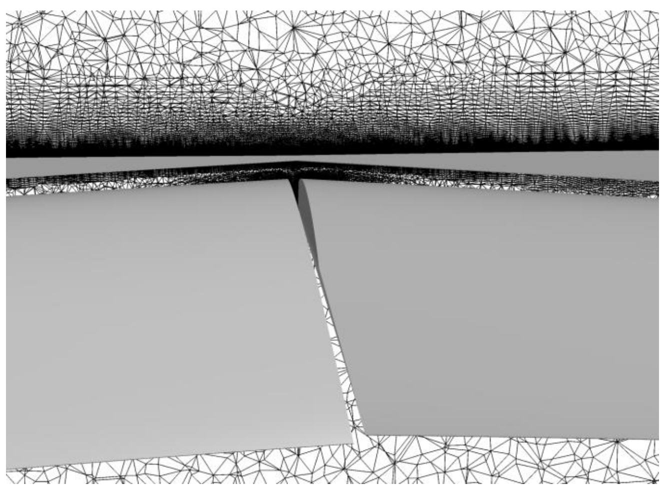
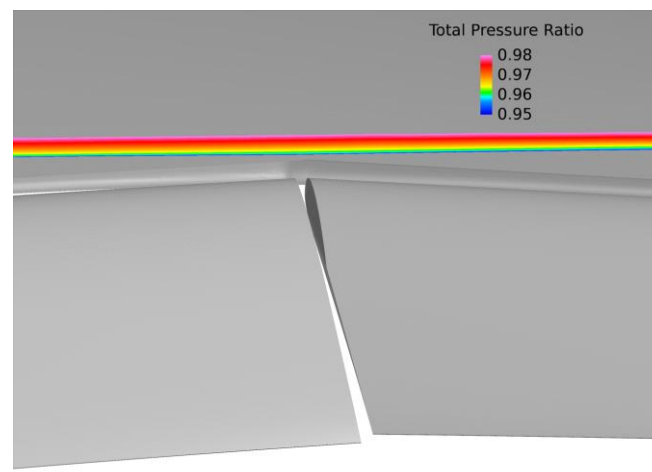


Comparison of Fixed and Adapted Meshes
Flap/Flap Full Gap, 16º Angle of Attack

Surface Mesh   *Cut Through Volume Mesh*   *Total Pressure Ratio Contours*

Adapted Mesh (52.4 M Nodes)

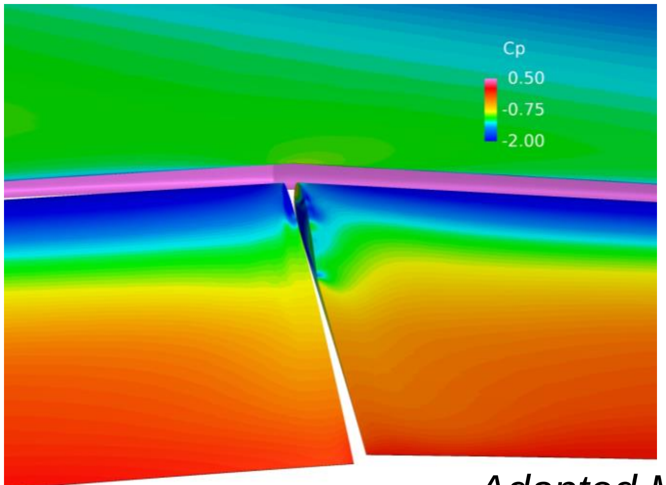




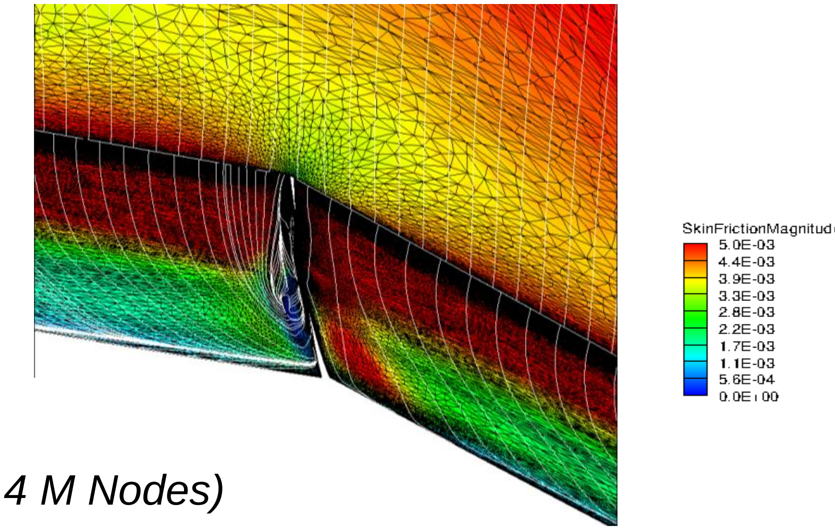
Fixed Fine Mesh (69.9 M Nodes)

Solution Comparison, Fixed and Adapted Meshes

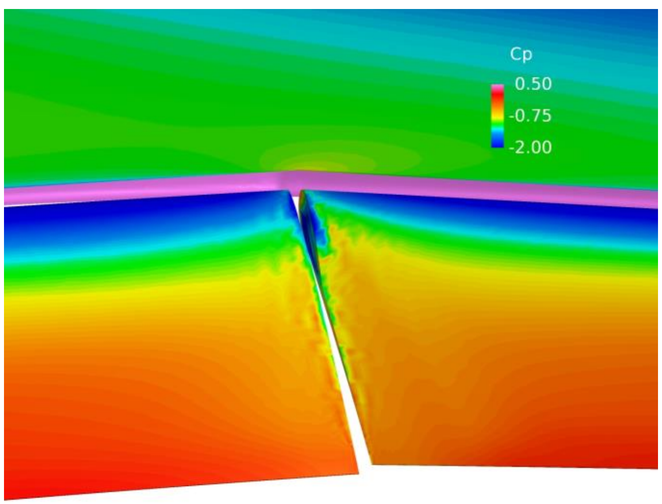
Flap/Flap Full Gap, 16º Angle of Attack

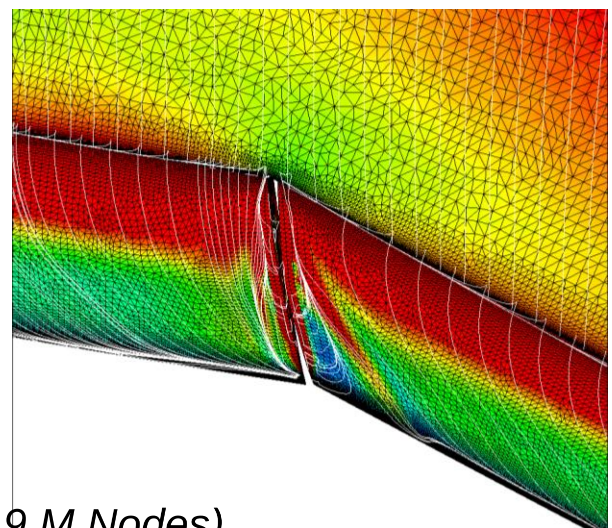
Surface Pressure Coefficient *Skin Friction and Oil Flow*





Adapted Mesh (52.4 M Nodes)





Fixed Fine Mesh (69.9 M Nodes)

JAXA Standard Model Adaptation Results

- All Cases Run Prior To HLPW-3
- Nacelle-On cases run in St Louis
- Nacelle-Off cases run in Seattle

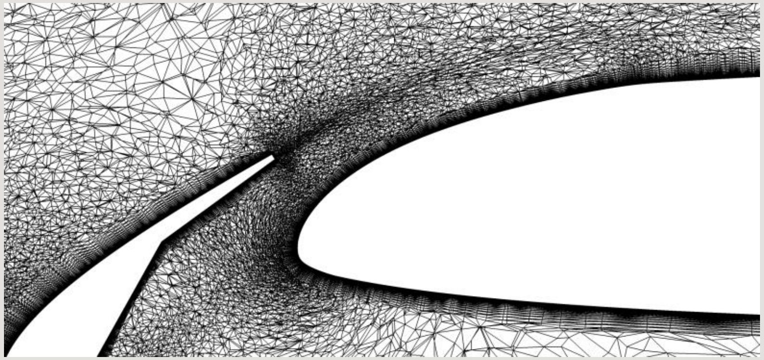
Summary of JAXA JSM Cases

- Adaptive and fixed mesh solutions computed on all cases

Grid System	Case Name	Case(s)
Committee (C1-JSM_UnstrTet_VGRID)	JSM Fixed Mesh	2a (nacelle off), 2c (nacelle on)
User (JSM_AdaptedTet_EPIC)	JSM Adapted Mesh	2b (nacelle off), 2d (nacelle on)

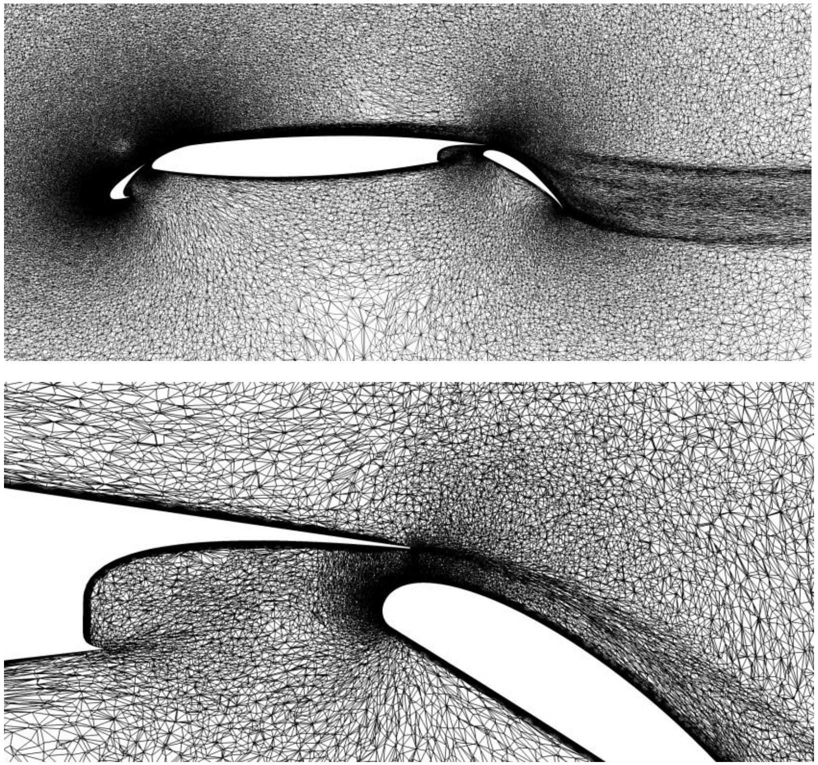
- Adaptive meshes
  - Nacelle on and off cases run independently with slight differences
  - Adapted to L^4 interpolation error of the Mach Hessian
  - 30% growth between adapted mesh levels (20% for Nacelle off)
  - Small number of near wall aligned mesh layers inserted into each adapted mesh to accelerate refinement of wall normal spacing

JSM Near Wall Mesh Insertion

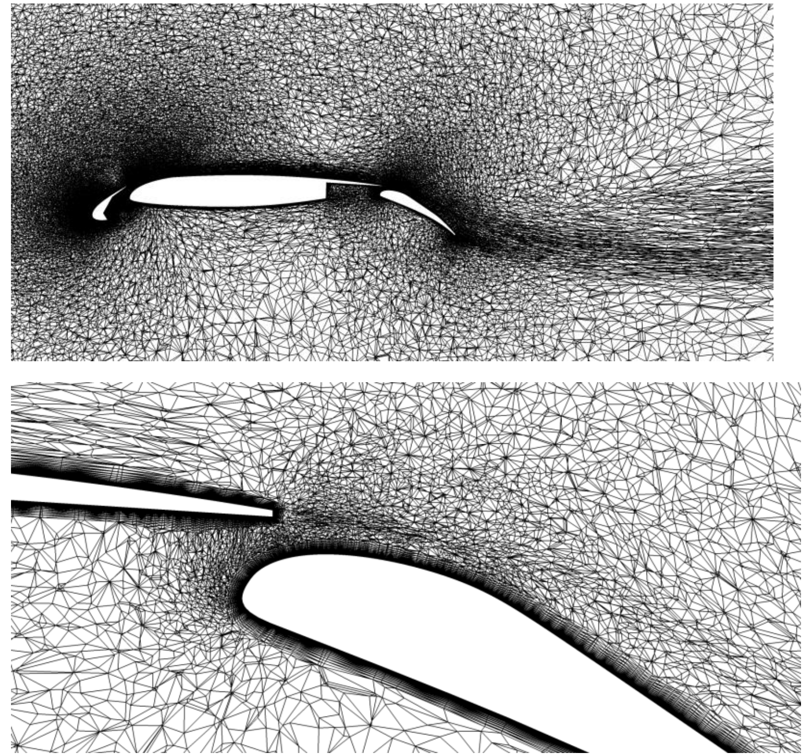


- Wall spacing adapted to y+=1.0
- 2 constant layers and 25 layers with 20% geometric growth (total height y+~=700)
- Fewer layers used for Nacelle off computations (total height y+~=300)
- Wall spacing/#layers ramped over first 6 mesh levels

Comparison of JSM and HL-CRM Adapted Meshes



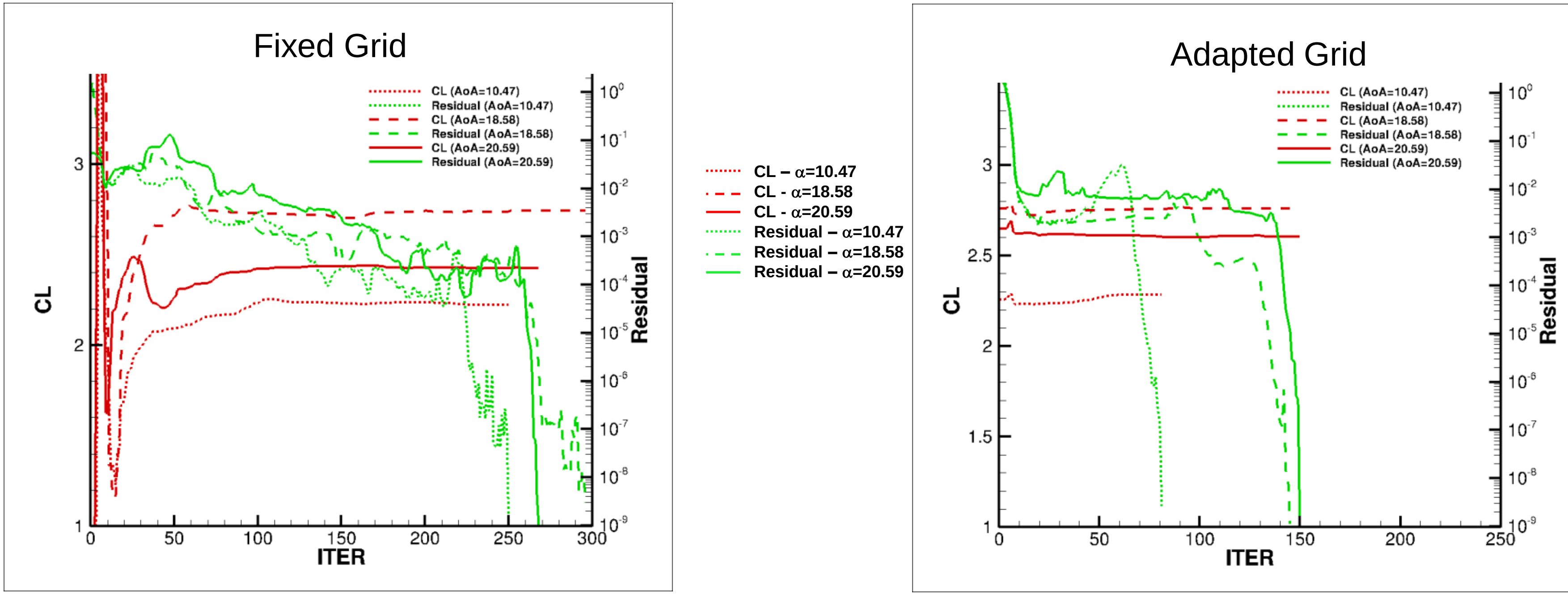
HL-CRM α=16^o Mesh (52.4 M Nodes)



JSM Nacelle On α=14.54^o Mesh (60.7 M Nodes)

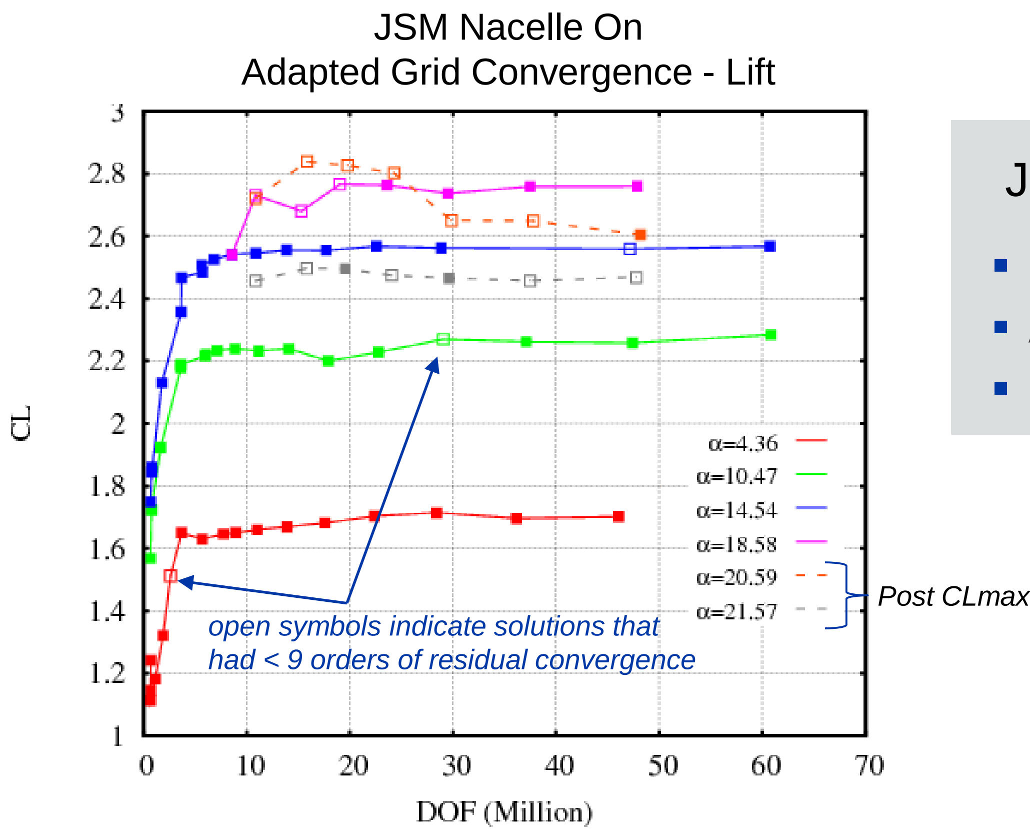
- **Geometric detail of JSM model requires more DOF to resolve**
- **Thicker JSM BL mesh uses more DOF**
- **Result – Less DOF available to resolve off body features compared to HL-CRM**

Sample GGNS Solution Convergence (JSM with Nacelle)



- Pre-stall angle of attack solutions converged well
  - Solution residuals converged 9 orders for almost all solutions
  - A few early/intermediate grid levels stalled at 7 orders of residual convergence
- Post stall solutions did not converge as well in general (5-6 orders of convergence)
- Adapted solutions required ~50% fewer iterations compared to fixed mesh solutions

JAXA JSM Nacelle On – Adapted Grid Convergence



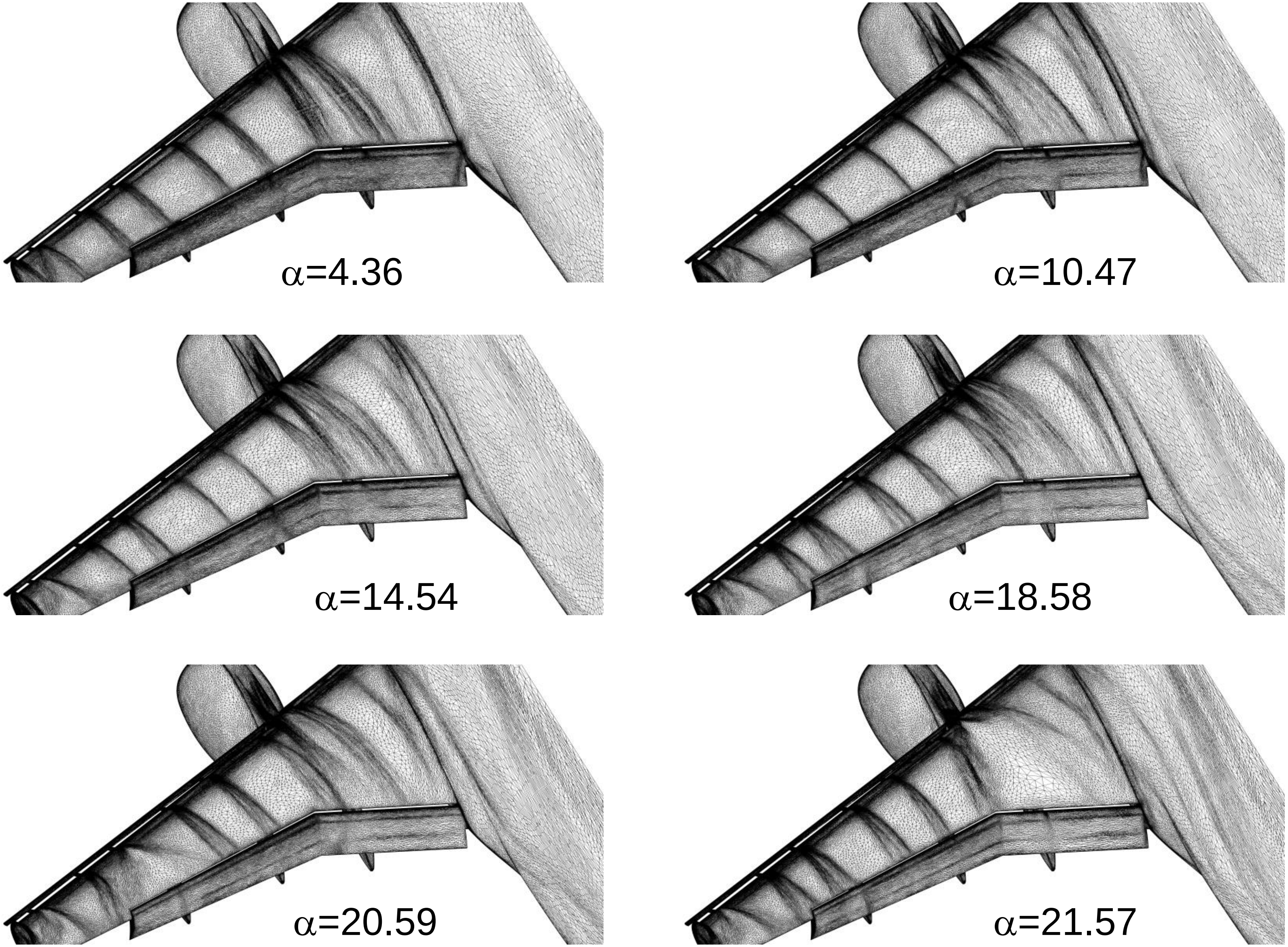
JSM Nacelle Off Process Differences

- Fewer layers of inserted near wall mesh
- Adaptation stopped after ~ 20M DOF
- Less "grid converged"

- Solutions up to 14.54º AOA initiated from freestream conditions on initial mesh
- Solutions > 14.54º initiated from intermediate mesh at previous AOA
- Rapid convergence to ~ 10M DOF followed by slow convergence to final lift
- Solutions above CLmax exhibit poorer residual convergence

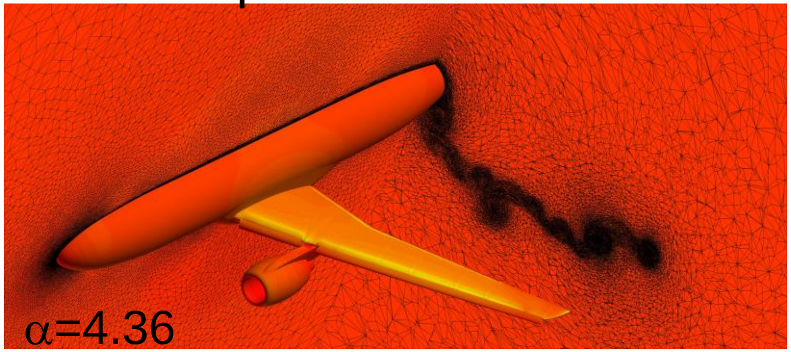
Adaptive Grid Generated at Each Solution Point

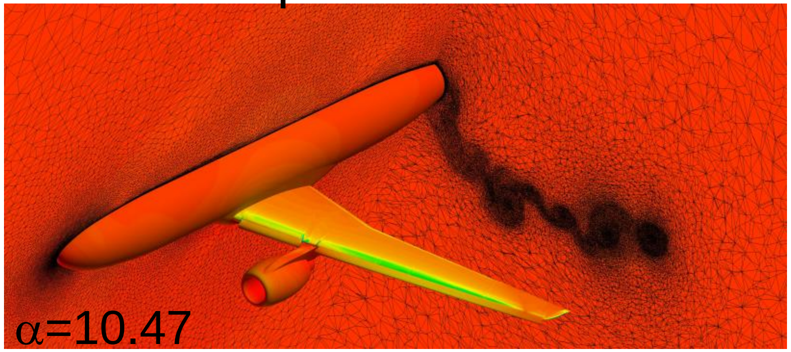
JSM Adapted Surface Grids for Angle of Attack Sweep

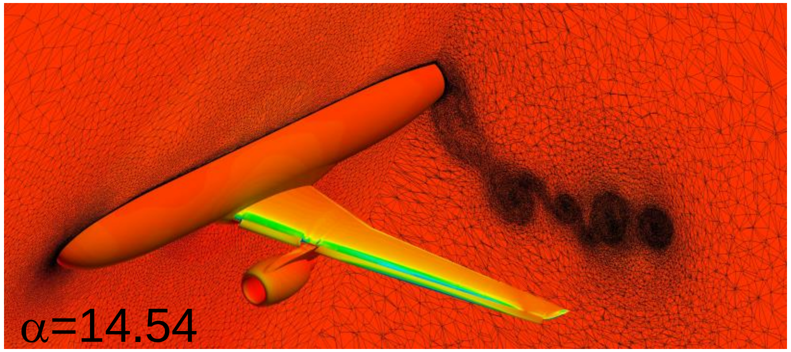


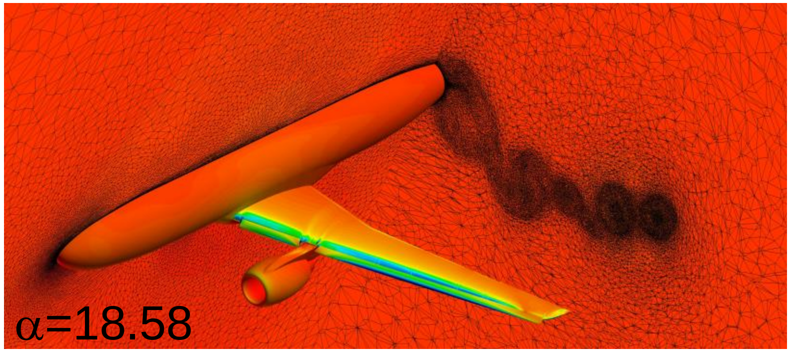
Adaptive Grid Generated at Each Solution Point

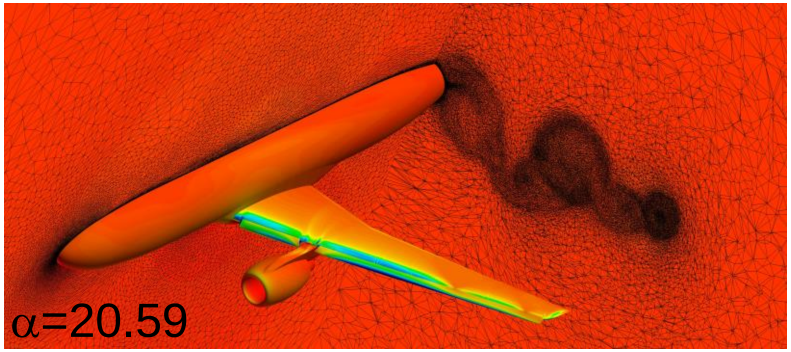
JSM Adapted Wake Grids for Angle of Attack Sweep

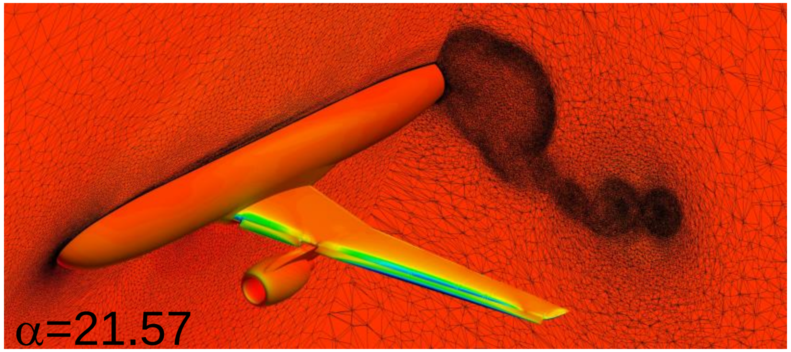










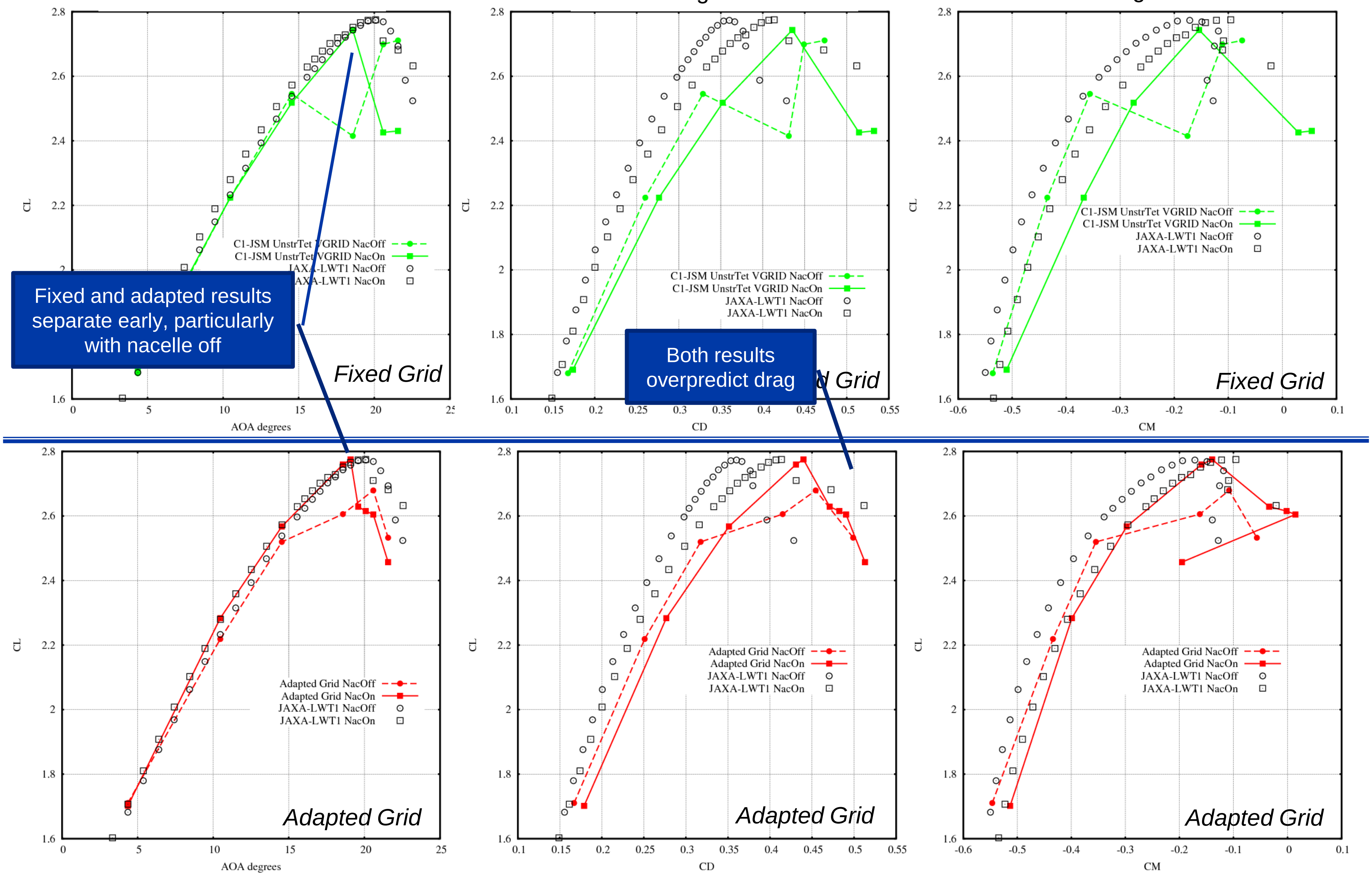


JSM Nacelle On/Off - Forces and Pitching Moment

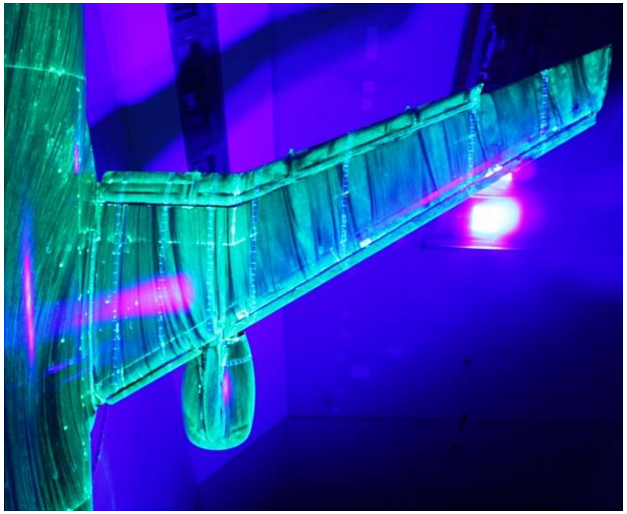
Lift Curve

Drag Polar

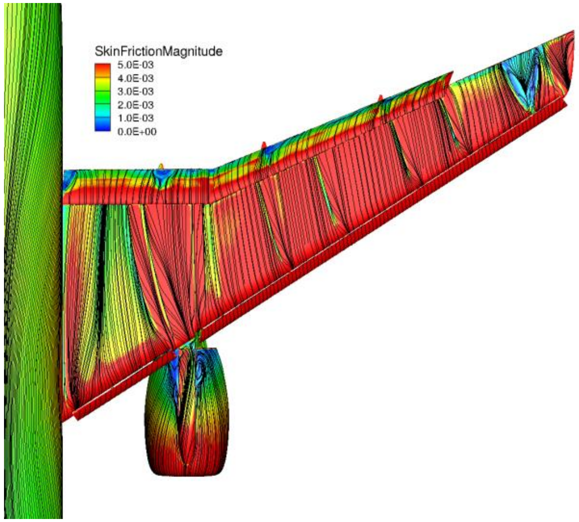
Pitching Moment



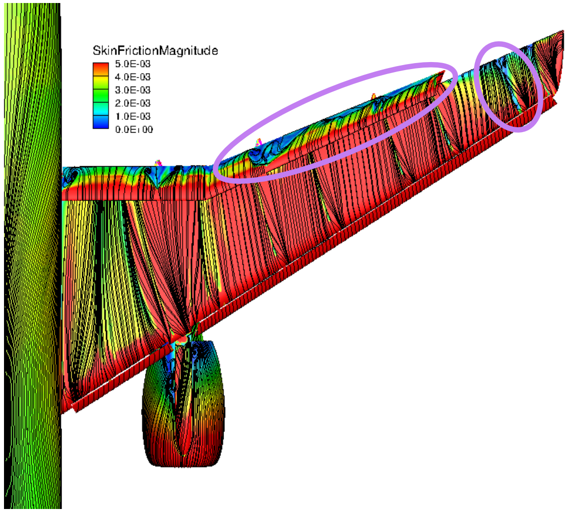
JSM Oil Flows AoA=4.36º



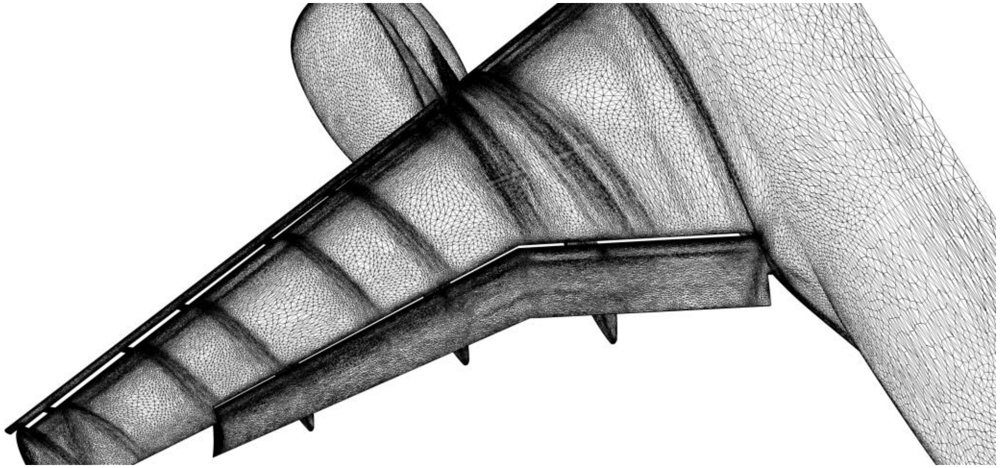
Test



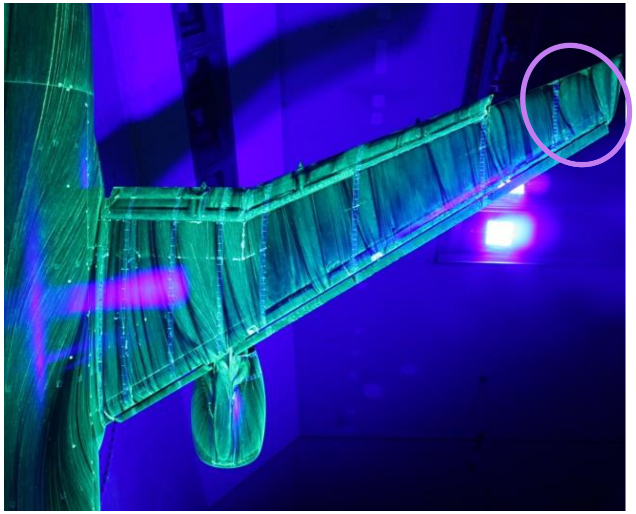
Adapted Grid



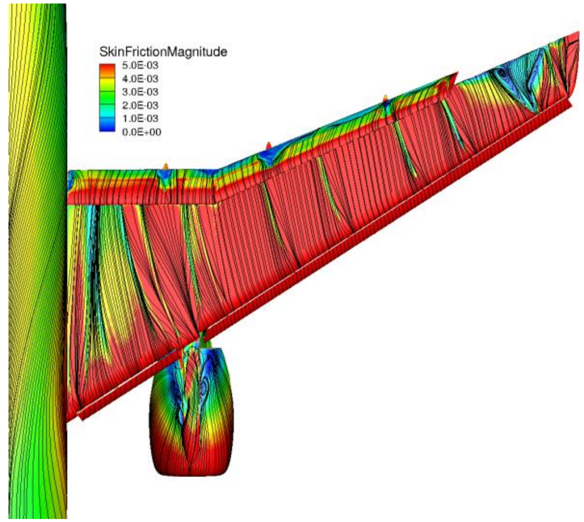
Fix Grid



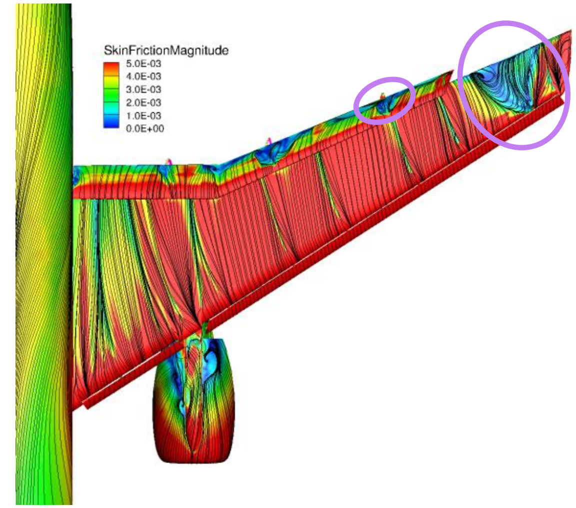
JSM Oil Flows AoA=10.47^{o}



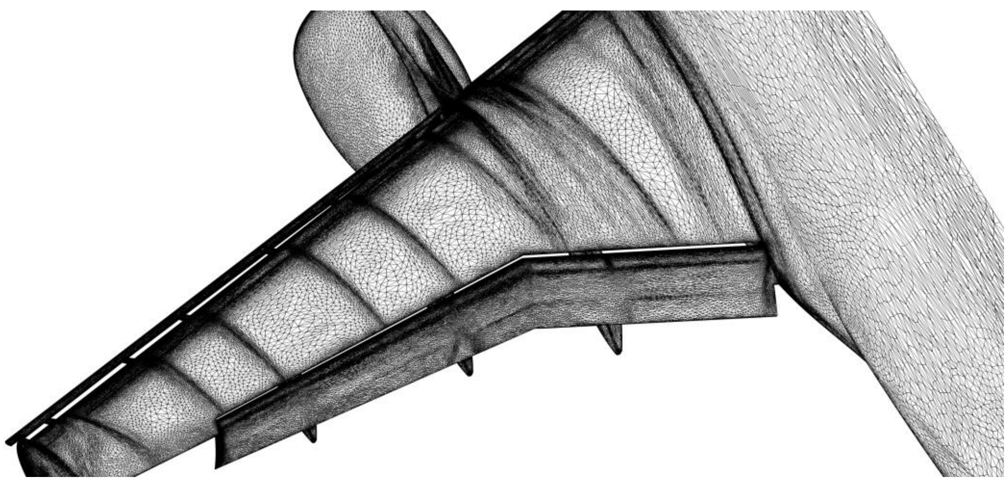
Test



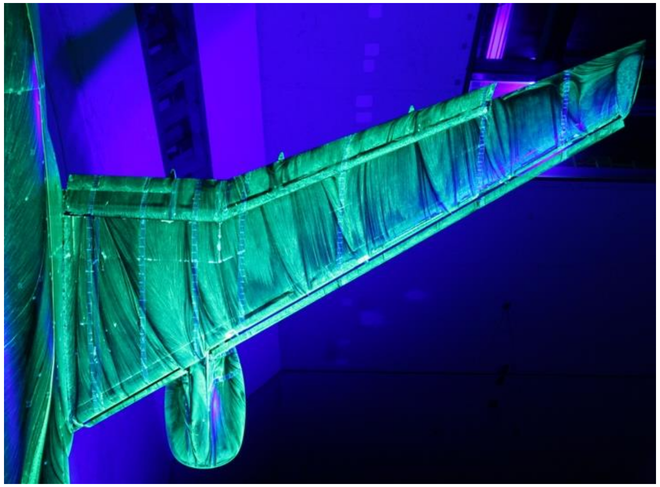
Adapted Grid



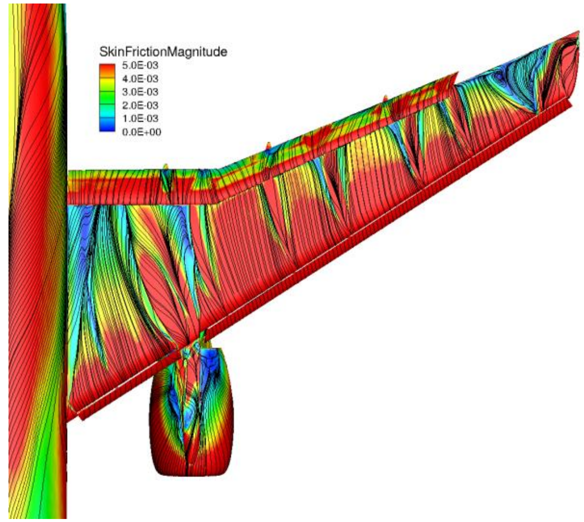
Fix Grid



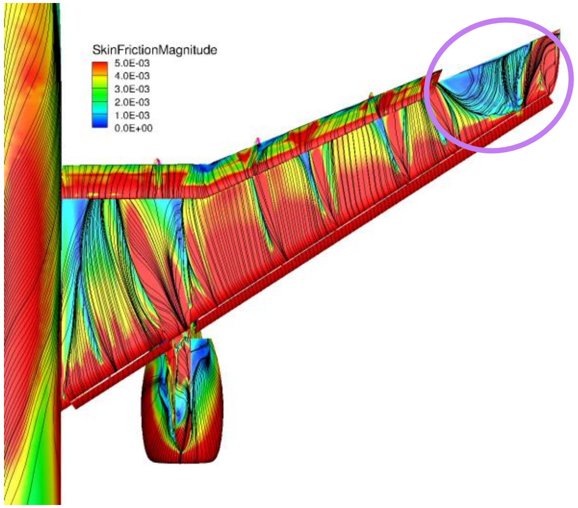
JSM Oil Flows AoA=18.59º



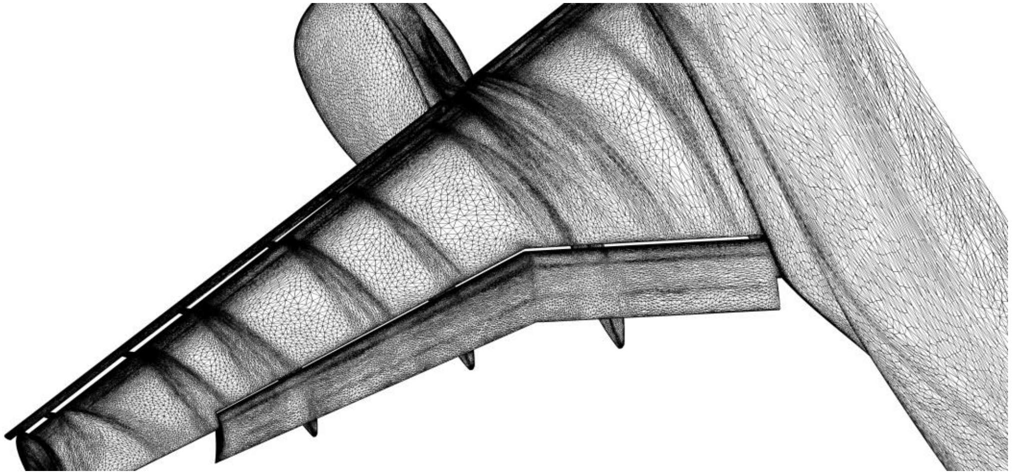
Test



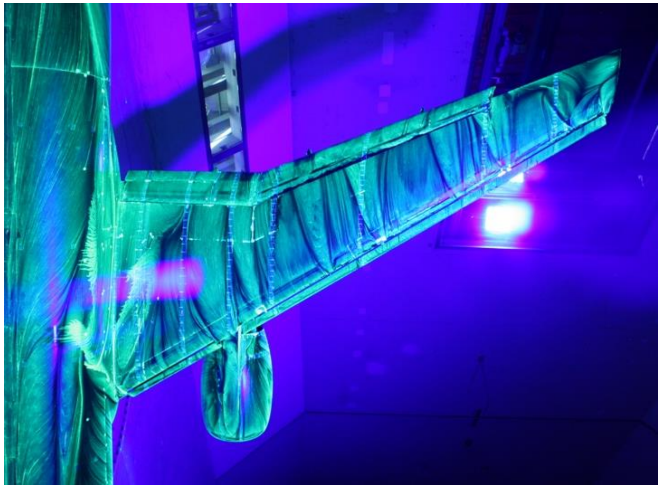
Adapted Grid



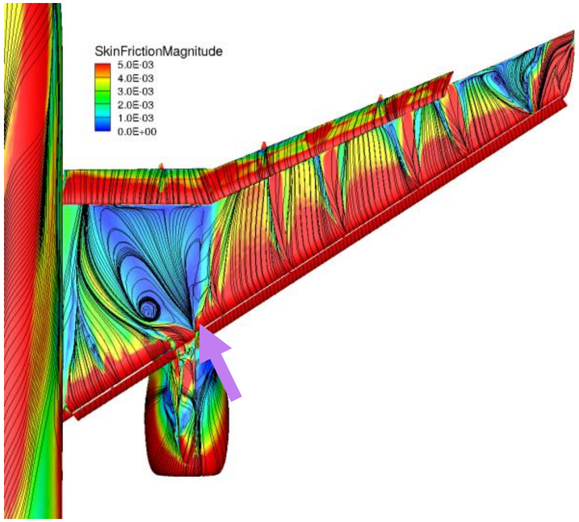
Fix Grid



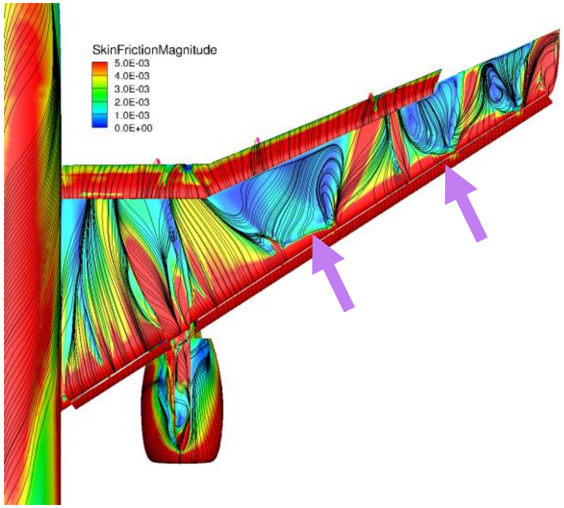
JSM Oil Flows AoA=21.57º



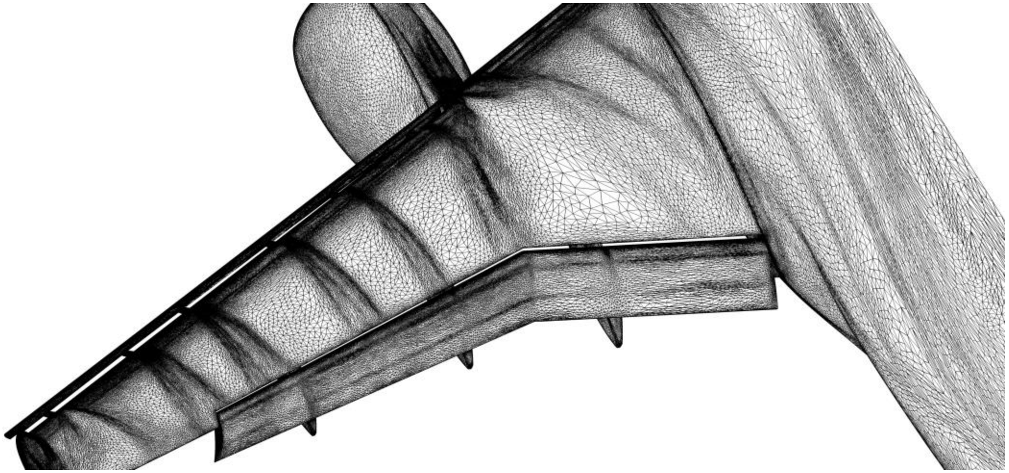
Test



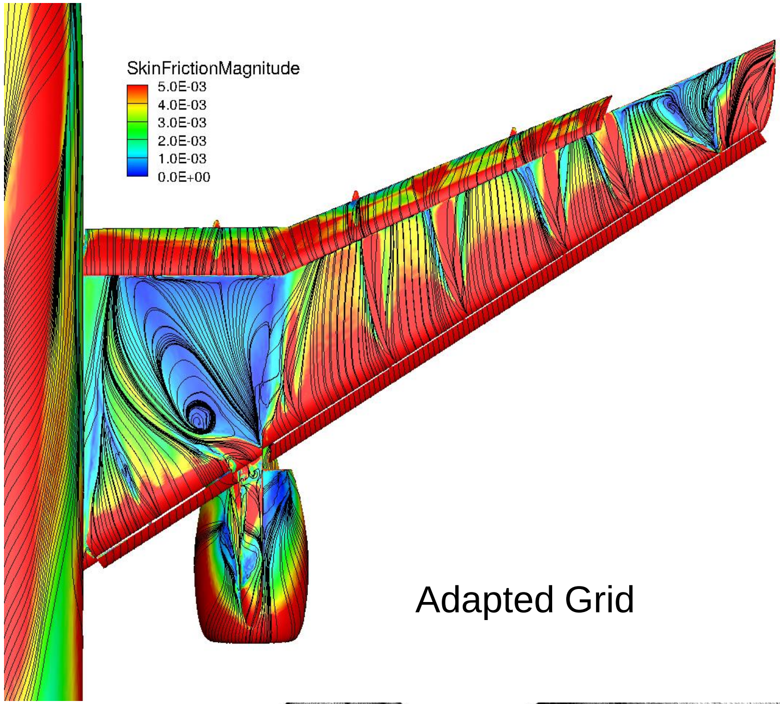
Adapted Grid

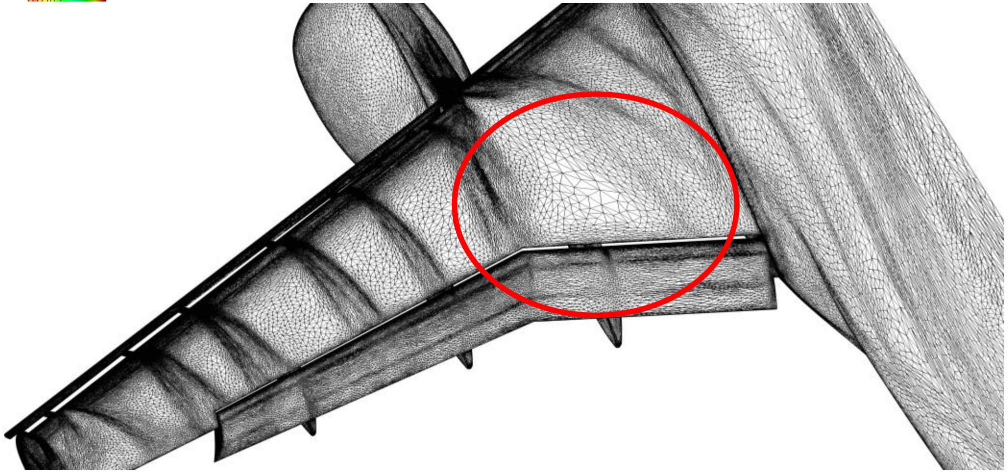


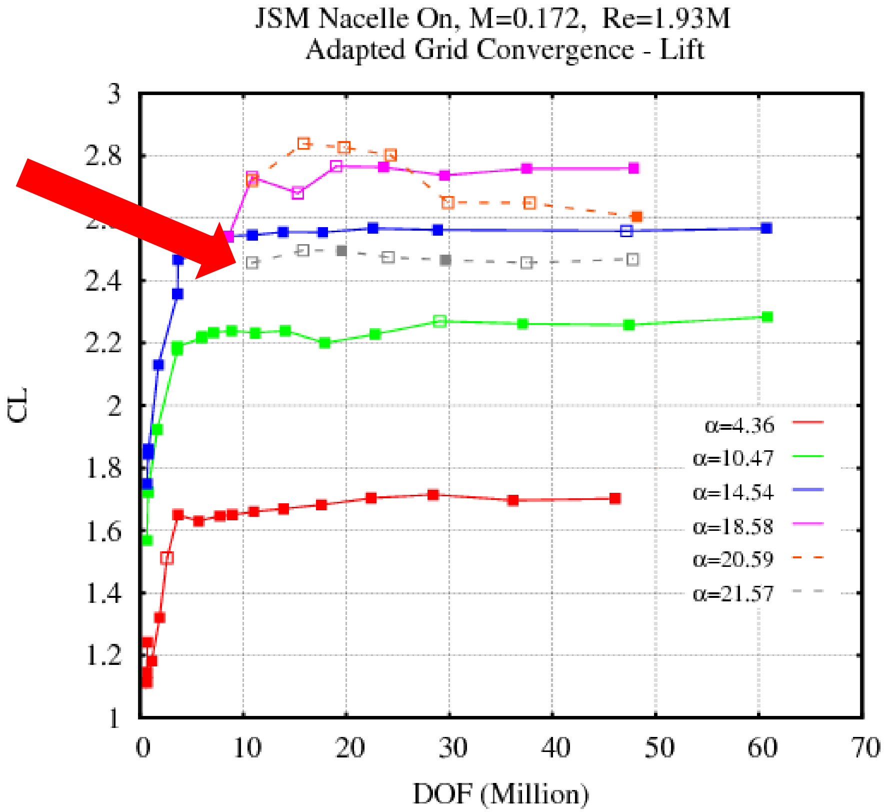
Fix Grid



JSM Oil Flows AoA=21.57°



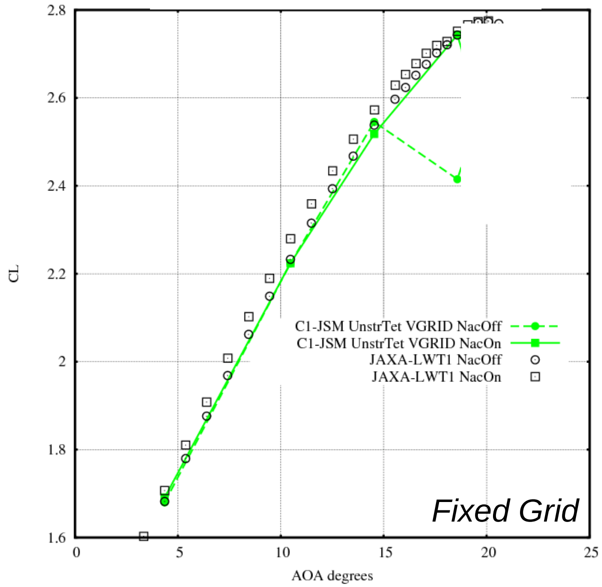




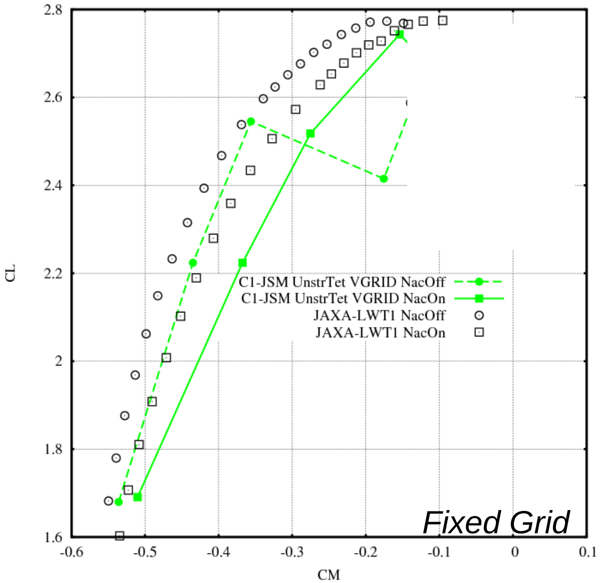
- Solution separated on initial mesh
- Adaptation coarsens mesh in separated region (Mach Hessian error estimate does not see the error)
- This may bias toward low lift solution and make it difficult to reattach in subsequent adapt cycles

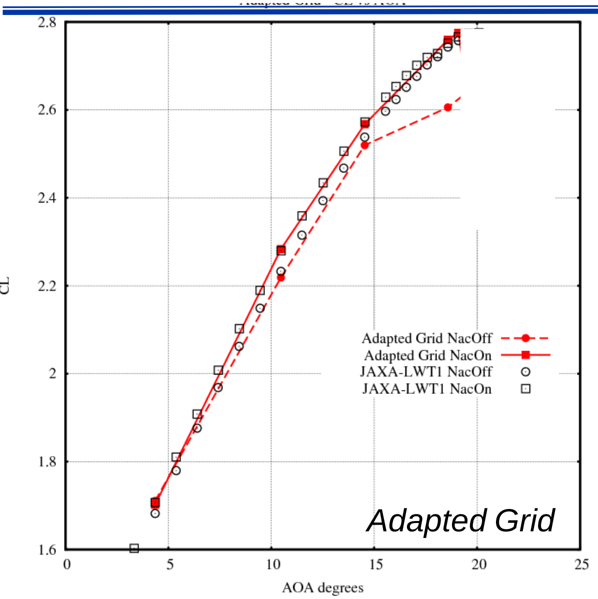
JSM Nacelle On/Off Forces – **Pre Stall**

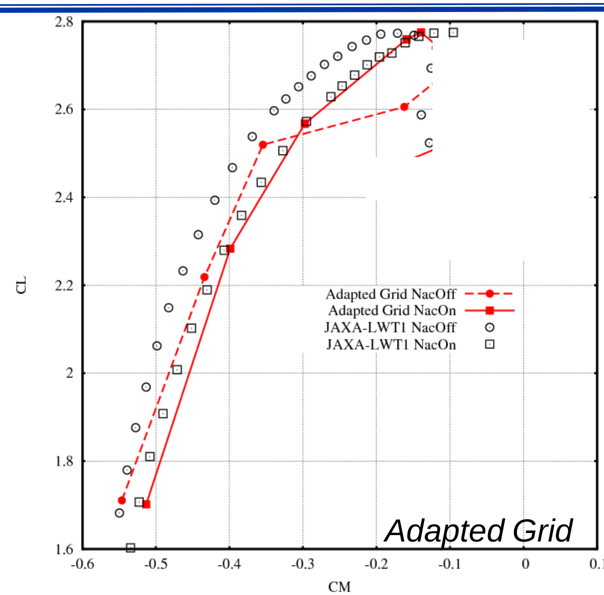
Lift Curve



Pitching Moment







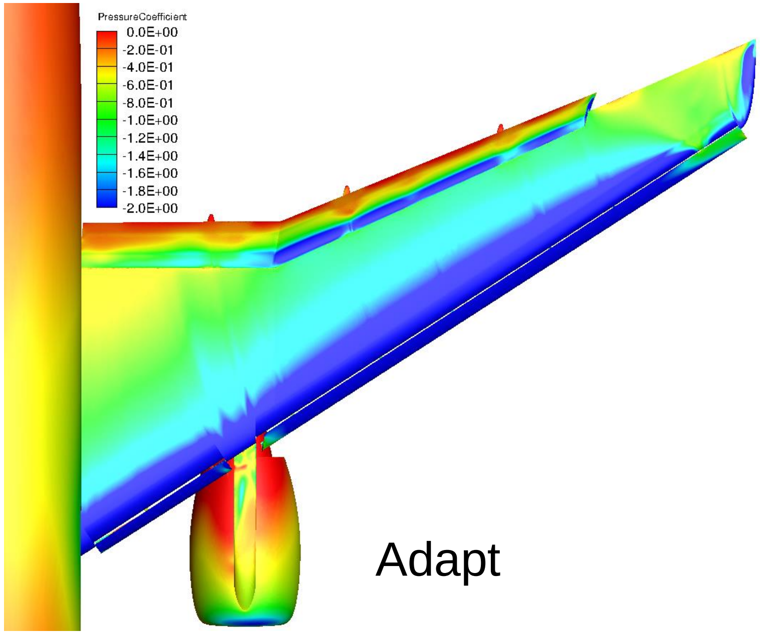
Adapted/Fixed Comparison

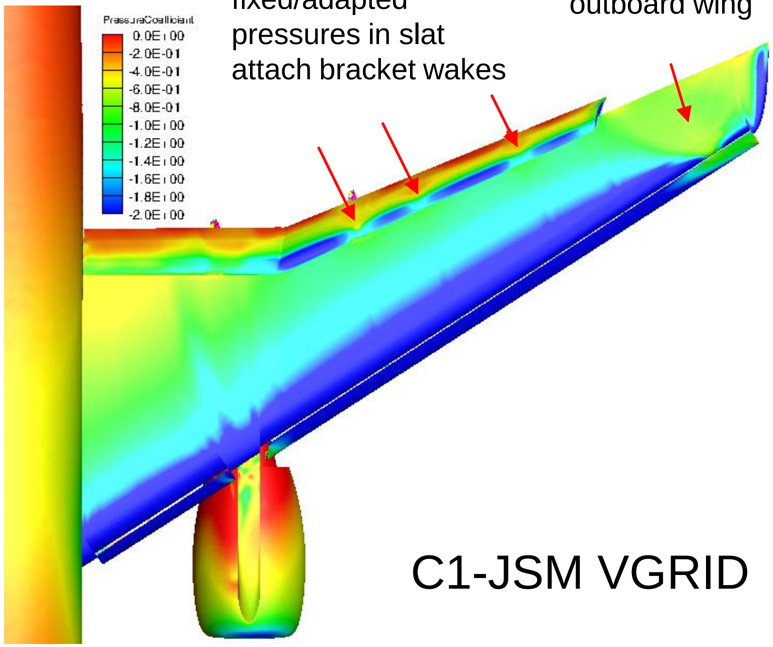
- Nacelle off results very similar for adapted/fixed meshes
- Adapted nacelle on results closer to data than adapted nacelle off results (increased resolution?)
- Adapted nacelle on/off increment closer to data

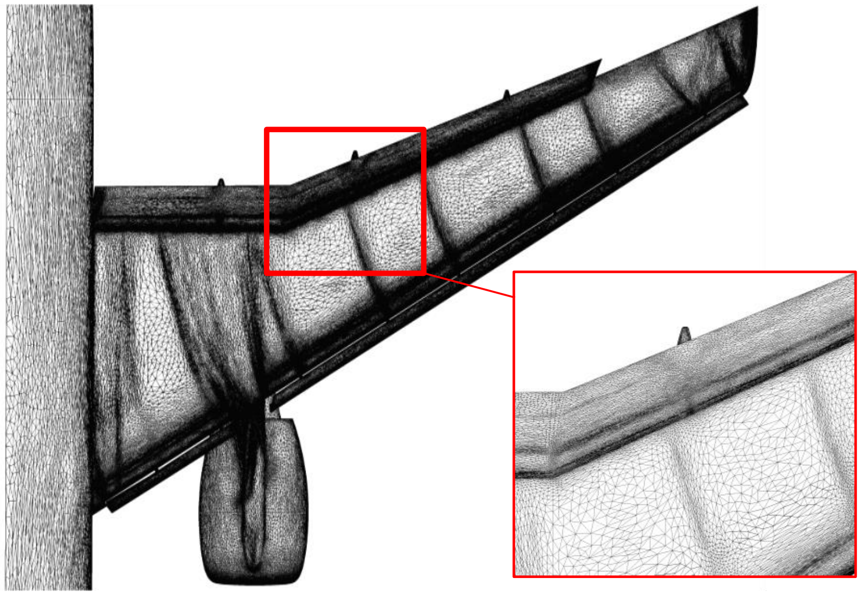
JSM with Nacelle AoA=14.54

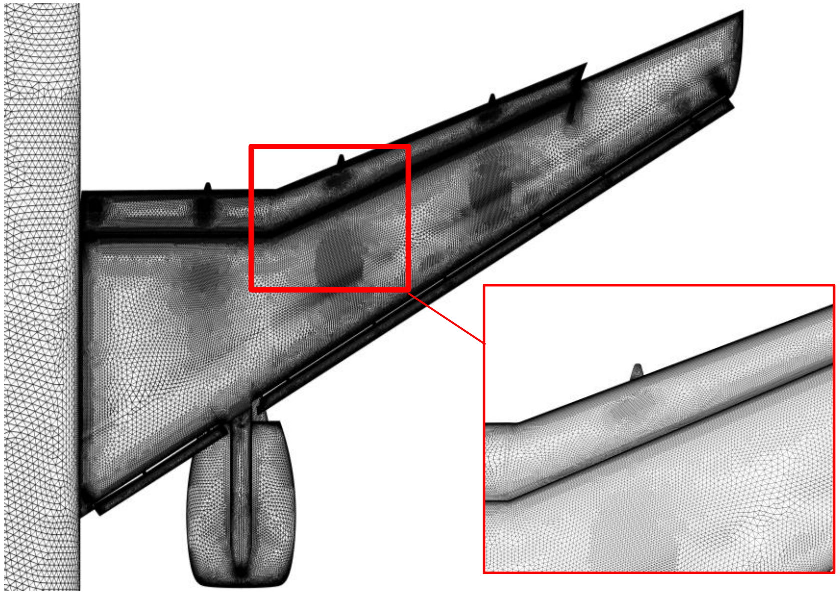
Different fixed/adapted pressures in slat attach bracket wakes

Larger separation on outboard wing

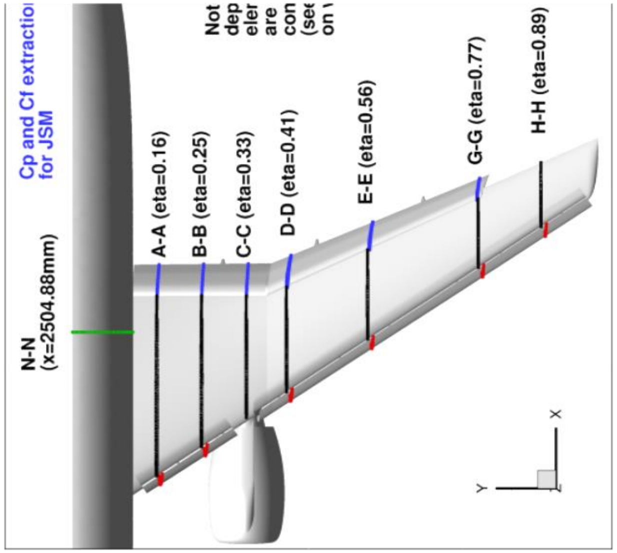


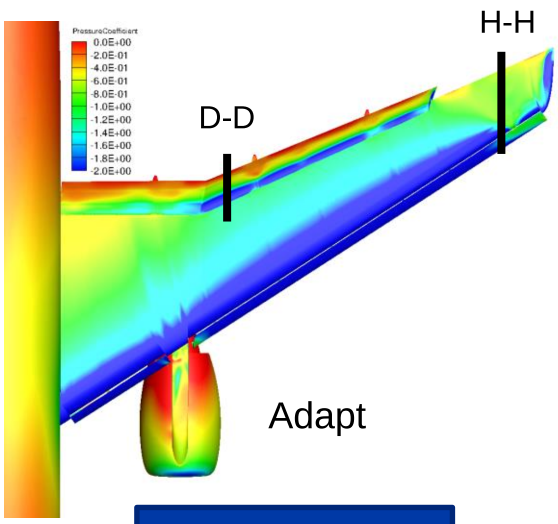


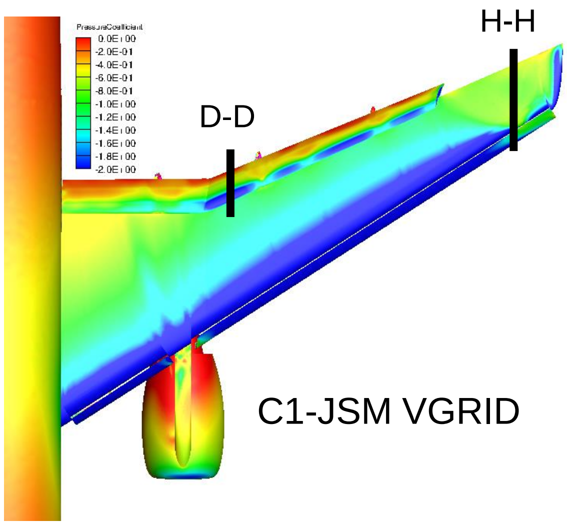




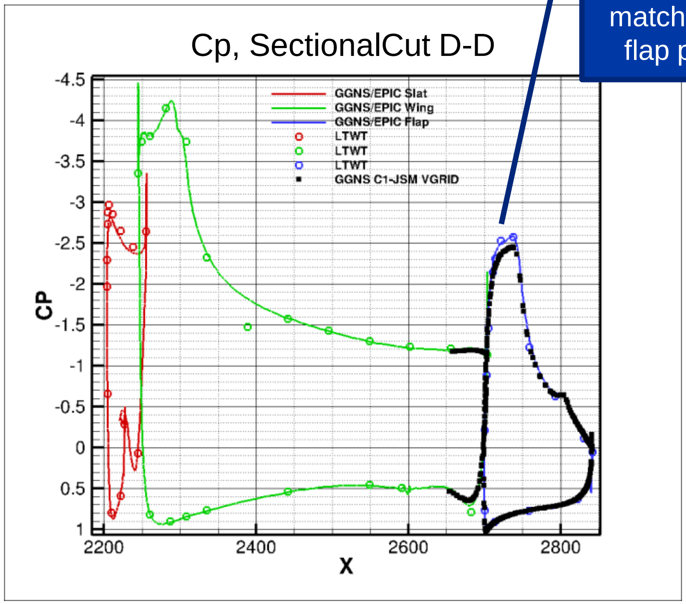
JSM with Nacelle AoA=14.54

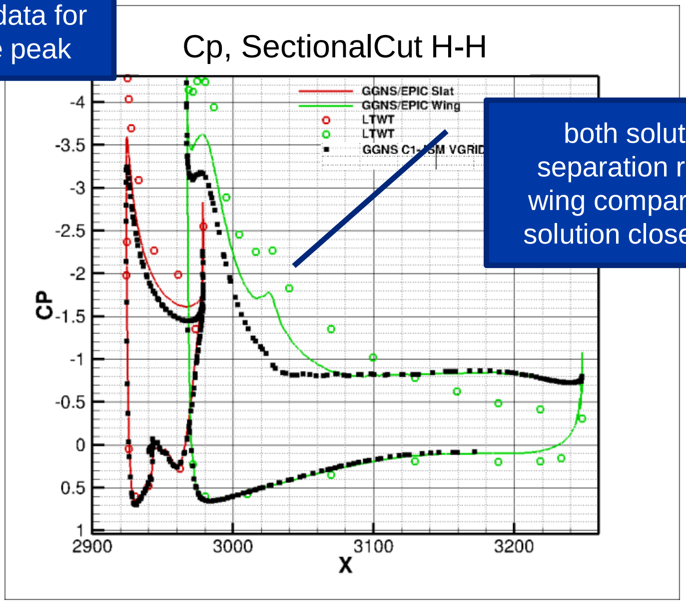






adapted grid solution matches test data for flap pressure peak



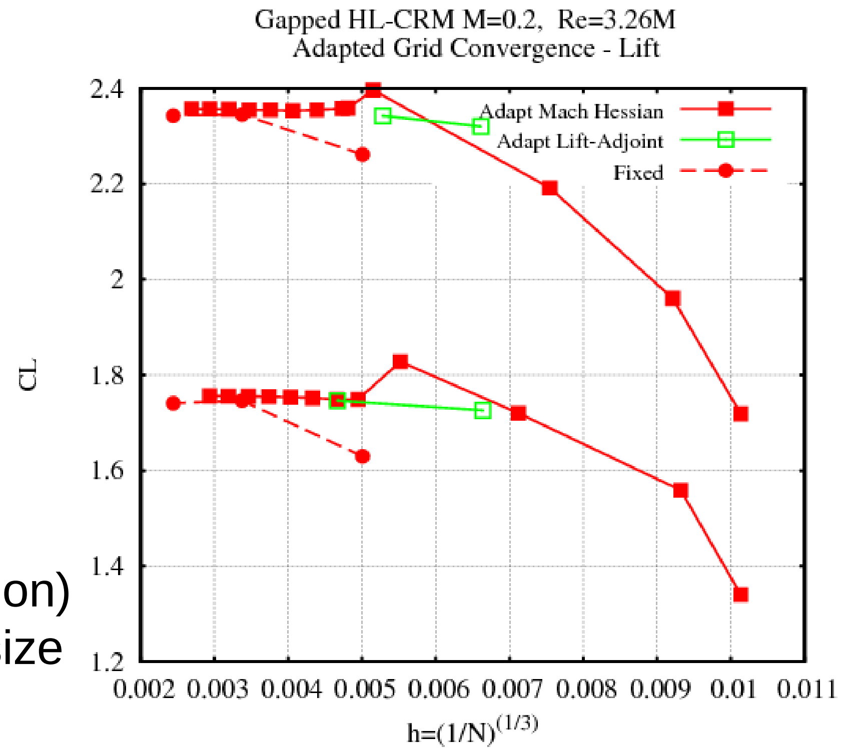


both solutions have larger separation region on outboard wing compared to test (adapted solution closer to test than fixed)

Summary

- **Adaptive Mesh Process**
  - ✓ Robust for HL-CRM and JSM cases
  - ✓ Full solution convergence for most pre-stall solutions and results approached constant lift with grid size for all cases
  - ✓ Automatic generation of mesh family in days (compared to weeks for fixed grid approach) with no a-priori solution knowledge required
- **HLCRM Results**
  - ✓ Near mesh converged results reached with relatively coarse mesh (15M nodes)
  - ✓ Good resolution in areas of tight geometric complexity
- **JSM Results**
  - ✓ Adaptation did not improve CLmax prediction
  - ✓ Adapted nacelle on results compared better with test data
- **Future Work**
  - ✓ Rerun JSM cases with latest EPIC/GGNS improvements and fewer mesh layers in BL
  - ✓ Investigate potential biasing due to separated initial mesh solution
  - ✓ Adaptation without BL insertion and with output error estimates

HL-CRM Output Error Adapted Solutions



- Output Error Estimate
  - Anisotropy from Mach Hessian
  - Adjoint solution provides estimated error in output (CL)
- Adaptation Process
  - Full adaptation to wall (no BL mesh insertion)
  - Multiple adaptation cycles at fixed target size
- Results
  - GGNS/EPIC solutions, Full Gap geometry 8º and 16º AOA
  - Improved mesh convergence particularly at low DOF

Thank you for your attention.